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Evaluation of Water Quality in Barkley Lake and Embayments with the BETTER 2-D Model

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BETTER, a two-dimensional mathematical water quality model, was used to simulate water quality conditions in the main-stem and two embayments of Lake Barkley. Sources and preparation of input data including reservoir and outlet geometry, meteorological conditions, model coefficients and inflow quality and quantity, are described. The report also outlines revisions to the model for the Barkley application, and calibration and verification procedures.

Three years, 1984-1986, were simulated under observed conditions and model predictions were compared to observed data. Additional simulations were performed to estimate impacts on water quality resulting from summer storm events, increased loadings of organic materials and nutrients, and the Cumberland Steam Plant. Knowledge gained from simulations with the model is summarized and recommendations for future applications and field studies are made.

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EVALUATION OF WATER QUALITY IN BARKLEY LAKE AND EMBAYMENTS WITH THE BETTER 2-D MODEL

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August 1989

ABSTRACT

Water quality conditions observed during 1984-1986 in Barkley Lake were simulated and evaluated with the two-dimensional reservoir water quality model, BETTER. Water quality profiles taken at stations along the Cumberland River mainstem and in embayments were used to test a branched version of the BETTER model that allows embayments to be included in the simulations. The variables of greatest interest were temperature, suspended sediment, dissolved oxygen, pH, nutrients and chlorophyll.

Barkley Dam is located at Cumberland River Mile (CuRM) 30.6 and the backwater extends 118 miles to Cheatham Dam at CuRM 148.7. At summer pool level of 359 ft. msl. the lake has a surface area of 58,000 acres and a volume of 0.87 million acre-feet. The long term average flow at Barkley Dam is approximately 28,000 cfs, so the average hydraulic residence time is 15 days. The Cumberland City Steam Plant is located in the upstream portion of the reservoir near CuRM 103. Lake Barkley is connected to Kentucky reservoir with a navigation canal located at CuRM 32.8.

Data from the summer of 1984 indicated that some DO depletion occurred in the main channel stations, with complete DO depletion observed in Little River embayment. Monthly sampling frequency missed several stratification and mixing episodes simulated by the daily model.

Several of the dominant water quality patterns observed during 1984 were approximately represented by the BETTER simulations, including the differences between main channel and embayment locations.

Validation of the model was demonstrated by simulating 1985 and 1986 conditions without changing any model coefficients. These simulations matched the available data equally well. The effects of increased loadings of organic materials and nutrients from point and non-point sources were simulated. The sensitivity of model parameters and inflow conditions on Lake Barkley water quality were determined.

The result of these investigations is a calibrated branched version of BETTER which provides an accurate characterization of water quality conditions in Barkley Lake. The model has been transferred to the Nashville District Corps of Engineers for routine use in planning and operational studies of the Cumberland River impoundments.

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INTRODUCTION AND OBJECTIVES

Water quality conditions have been generally good, with few reported pollution episodes or issues of concern in either the Tennessee or Kentucky portions of Lake Barkley. Nevertheless, as part of a basin-wide effort by the Nashville District Corps of Engineers to investigate and provide controls for water quality in the Cumberland River impoundments, a study of water quality in Barkley Lake was initiated. Murray State University was contracted to provide field surveys throughout the lake (King and Jarrett, 1988). Tennessee Technological University was contracted to apply the BETTER 2-D water quality model to Barkley Lake. Conditions in the embayments as well as the mainstem portion of the lake were investigated and modeled.

Water quality conditions observed during 1984-1986 in Barkley Lake were simulated and evaluated with the two-dimensional reservoir water quality model, BETTER. Field data collected by Murray State University for the Nashville District Corps of Engineers provided the basis for model calibration and validation. Water quality profiles taken at several stations along the Cumberland River mainstem and in several embayments were used to test a branched version of the BETTER model that allows embayment volumes to be included in the simulations. This report documents these investigations of Barkley Lake water quality using the branched BETTER model. Project tasks included 1) development of a branched version of the BETTER model, 2) application of the BETTER model to Barkley Lake, 3) calibration of the model results with 1984 field data, 4) verification of the model results with 1985 and 1986 field data, and 5) demonstration of model sensitivity to coefficients and inflow conditions, and

6) recommendation of additional Lake Barkley model simulations and data collection efforts.

Since releases from Cheatham Dam (CuRM 148.7) into Lake Barkley are near equilibrium temperature, and velocities are relatively high, the upstream reaches of Barkley do not stratify. However, downstream of the Cumberland City Steam Plant (CuRM 103), weak intermittent stratification events have been observed. Although the vertical temperature differences are typically less that 3° C, the vertical density differences have been sufficient to prevent complete vertical mixing and allow dissolved oxygen concentrations to decrease in the hypolimnion. The temperature stratification in the embayments is slightly stronger, while the DO depletion in the embayments is much stronger. The model was used to investigate possible explanations for these differences.

One of the water quality variables of greatest concern in Barkley Lake is dissolved oxygen (DO). Releases from Cheatham Dam can have relatively high concentrations of organic materials and nutrients due to the wastewater treatment plant effluent discharges from the Nashville Metropolitan area. The relatively large local watershed areas (~438 mi^2) can also contribute high loadings of suspended sediment, organic materials, and nutrients during storm runoff events. The effects of these various inflow loading sources on Barkley Lake water quality were investigated with several model simulations of possible inflow conditions.

Primary production from suspended algal populations is the basis for the aquatic foodweb and fishery production within Barkley Lake. The algal populations require an adequate nutrient supply and sufficient light for optimal growth conditions. The model was used to investigate the status of algal primary productivity (measured by increases in surface pH) and standing crop (measured as chlorophyll), and to stimulate the effects of possible inflow conditions on

resulting algal populations. High suspended sediment (SS) inflows limit light conditions, but the accompanying nutrients may stimulate algal growth once the SS particles settle sufficiently in downstream segments. Algal growth increases surface DO concentrations, but the increased organic matter may consume DO as it settles to lower layers of the lake and respires or decays. The primary variables of interest in this study were, therefore, temperature, DO, SS, pH, nitrate, phosphorus, and chlorophyll.

BARKLEY LAKE DESCRIPTION

Lake Barkley is formed by Barkley Dam and is the most downstream reservoir on the Cumberland River. The project was completed in 1966 by the Nashville District Corps of Engineers as part of the comprehensive development of the Cumberland River basin for flood control, navigation, power generation, and recreation. The lake is also used for wildlife management, sport and commercial fishing, municipal and cooling water supply, and receives waste effluents and thermal discharges.

Cumberland River Watershed

The Cumberland River basin is crescent shaped, with the Cumberland River flowing in an arc from southeastern Kentucky down into middle Tennessee past Nashville and then back north into western Kentucky to join the Ohio River near Smithland, Kentucky. The entire basin includes 17,914 square miles and the river is almost 700 miles long as shown in Figure 1. Barkley Dam is located at Cumberland River mile (CuRM) 30.6 near Grand Rivers, Kentucky, and has a drainage area of 17,598 square miles. Streamflow at Barkley Dam (including diversions from the Tennessee River) is estimated to average approximately 28,000 cfs (1.6

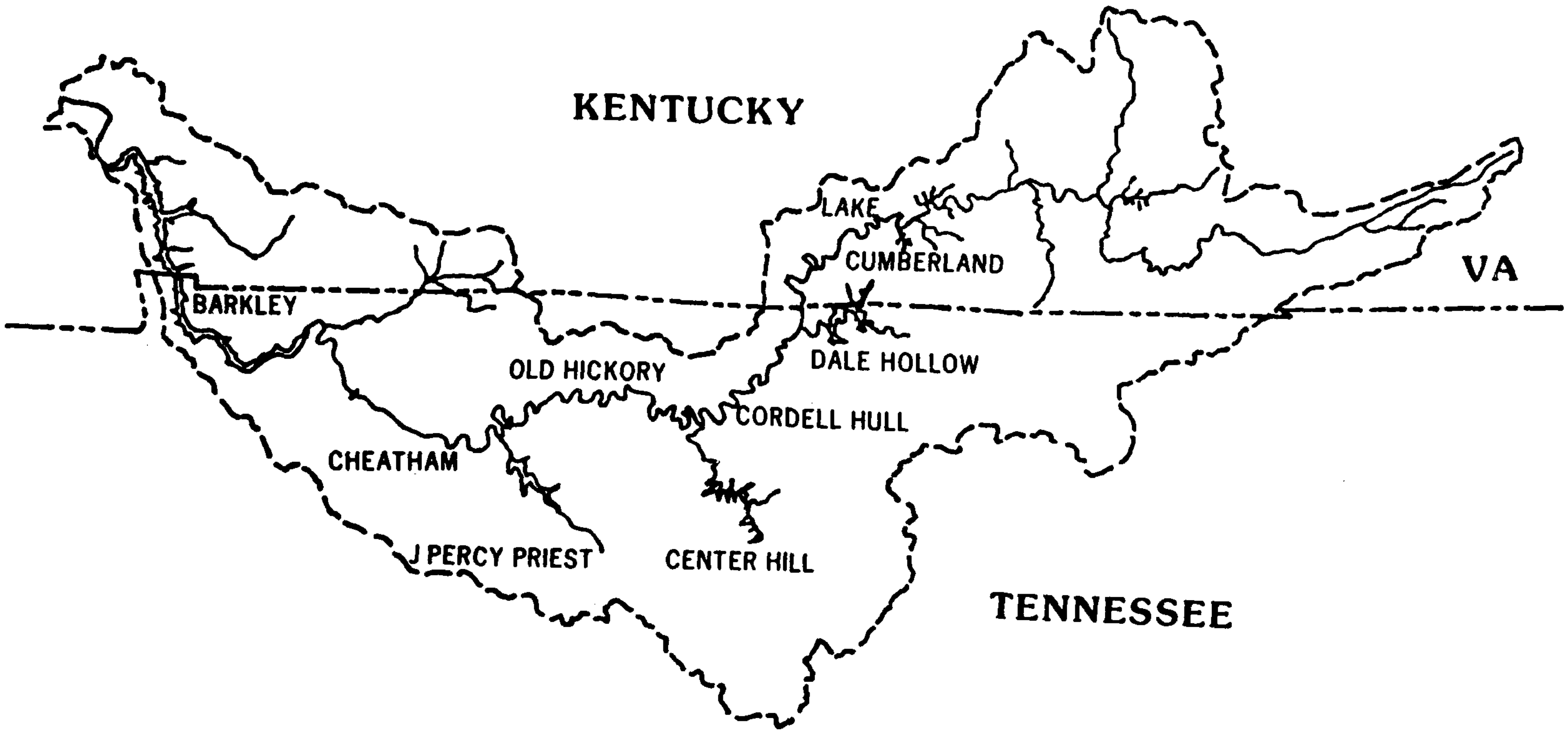


Figure 1 Cumberland River Basin

cfs/mi^2). Cheatham Dam is located a CuRM 148.7 near Ashland City, Tennessee, and has a drainage area of 14,160 square miles. The uncontrolled drainage area to Barkley Lake is therefore 3438 square miles. This local inflow enters from several major tributary streams including the Red River (1465 square miles), Yellow Creek (175 square miles), Little River (601 square miles), and Eddy Creek (107 square miles). The embayments formed by Eddy Creek and Little River are quite large since they enter Barkley Lake in the downstream portion of the reservoir. These two tributary embayments were included in the Barkley Lake version of the branched BETTER model.

Barkley Dam and Powerhouse

Barkley Dam is a combination rolled earth-fill and concrete gravity structure that rises approximately 110 feet above the streambed. The length is approximately 10,000 feet, with 1,250 feet of concrete structures including the spillways, powerhouse and lock facilities. The lock provides a normal lift of 57 feet from tailwater elevation 302 ft. msl. to summer pool elevation of 359 ft. msl. The powerhouse contains four turbines that have a combined maximum flow capacity of 55,000 cfs, producing approximately 130 MWe of electricity. The generation schedule generally follows peaking power demands, so release flows often vary significantly during the day.

Barkley Lake Geometry

Barkley Dam is located at Cumberland River mile (CuRM) 30.6 near Grand Rivers, Kentucky. Lake Barkley extends 118 miles to Cheatham Dam at CuRM 148.7, near Ashland City, Tennessee. At summer pool level of 359 ft. msl. the lake has a surface area of 58,000 acres and a volume of 0.87 million acre-feet with a maximum depth of 80 feet and a mean depth of about 15 feet. At the normal winter

pool elevation of 354 ft. msl. the lake has a surface area of 45,000 acres and a volume of 0.61 million acre-feet with a mean depth of 13.5 feet. During flood control operations, the water surface elevation can rise to 375 ft. msl. with a storage volume of 2.08 million acre-feet. The reservoir is quite narrow and riverine in the upstream portion, and only slightly wider in the downstream segments. There are several small creek embayments and overbank areas, with two relatively large embayments formed by Little River and Eddy Creek.

The BETTER model was modified from previous applications for Old Hickory and Cheatham Lakes to include branches or embayments. This allows these important regions of reservoirs to be included in simulations of water quality conditions. Because the contributing watershed areas of embayments are often small compared to their water volumes, residence times are longer and stratification can be stronger. One of the objectives of this study was to determine how accurately the branched version of BETTER would reproduce observed water quality patterns in the Little River and Eddy Creek embayments of Barkley Lake.

Hydrology and Operations

The long term average flow at Barkley Dam is approximately 28,000 cfs, so the average hydraulic residence time is 15 days. Lake Barkley is connected to TVA's Kentucky reservoir with the Barkley-Kentucky canal, located at CuRM 32.8. This canal requires that the two reservoirs be operated in a coordinated manner, although significant flows can move through the canal during flood control operations or whenever there is an elevation difference between the two reservoir pools. The normal operations involve a winter pool elevation of 354 ft. to provide flood control storage capacity. The pool elevation of the two reservoirs

is generally raised to 359 ft. during April, and gradually lowered from mid-June through October, as shown in Figure 2. However, this seasonal pattern may be modified and adjusted each year depending on the hydrologic conditions encountered.

The daily inflows and outflows together with the seasonal fluctuations in reservoir elevations (storage volumes) determine the water budget for Barkley Lake. Since each year represents slightly different hydrologic conditions, it is quite informative to calculate the residence time patterns for each year of operation. The residence time is the combination of reservoir volume and flow patterns, and is useful for interpreting the potential for water quality changes since the magnitude of many effects depends on the duration of the processes which produce the effects. These seasonal outflow and residence time patterns for Barkley Lake from 1966 through 1987 are shown in Figure 3. The residence time patterns indicate the magnitude of extended low flow periods and the flushing effect from high flows.

By comparing the different years, it was possible to evaluate how representative the study years 1984, 1985, and 1986 were. Since longer residence times represent an opportunity for stratification, DO depletion, suspended sediment settling, nutrient uptake and algal growth processes, episodes of residence time greater than thirty days (twice the average residence time) can be considered critical for Barkley Lake. If these long residence times occur during the summer period, then the probability of water quality changes is greatest. Many years had a very constant pattern of low residence time, reflecting the large amount of upstream flow regulation without any major basin scale flood flow events. Most of the years had residence times of 5-10 days in the winter and 20-30 days in the summer period. Other years had extended periods

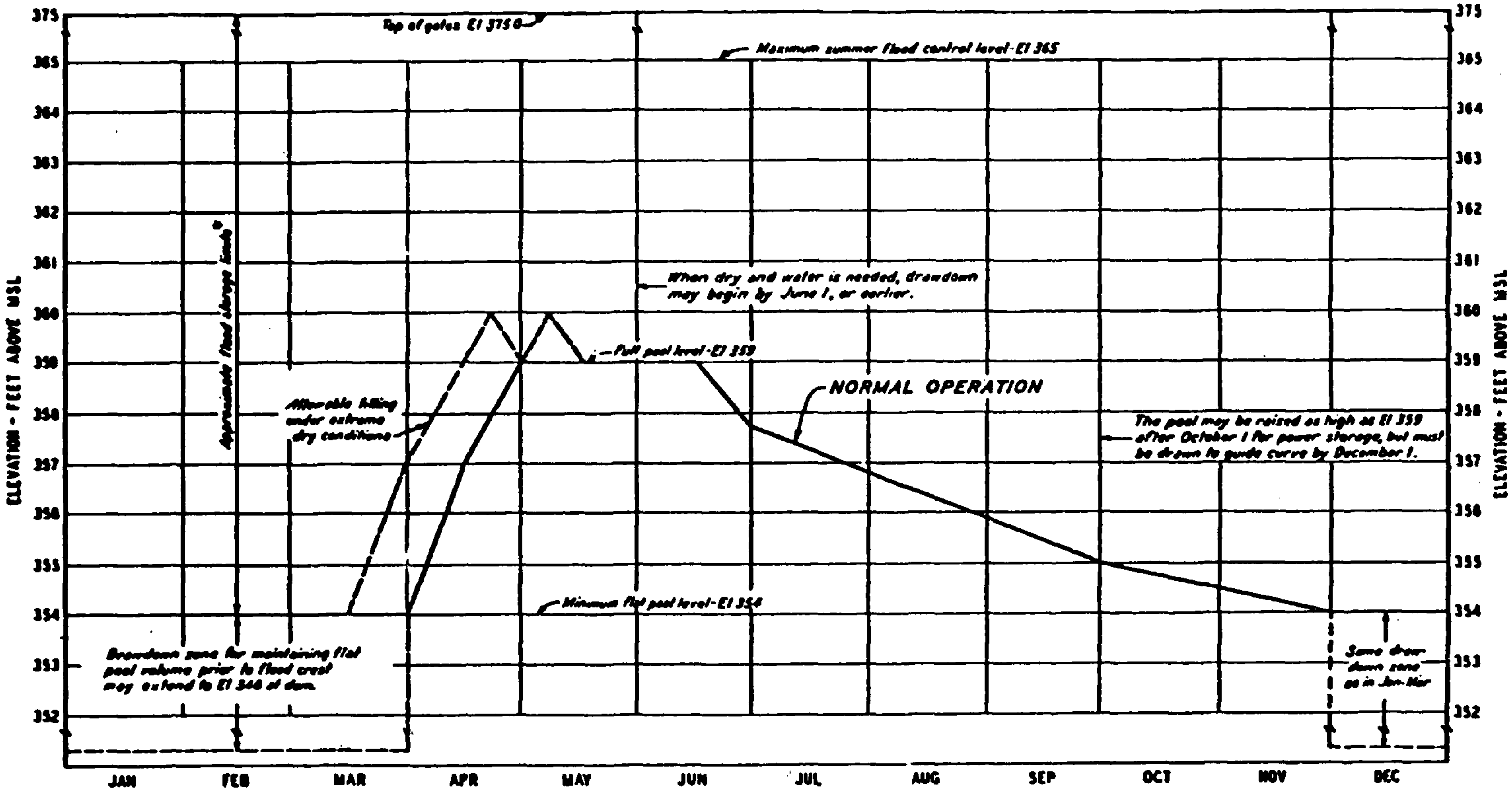


Figure 2 Barkley Lake Normal Surface Level Operations

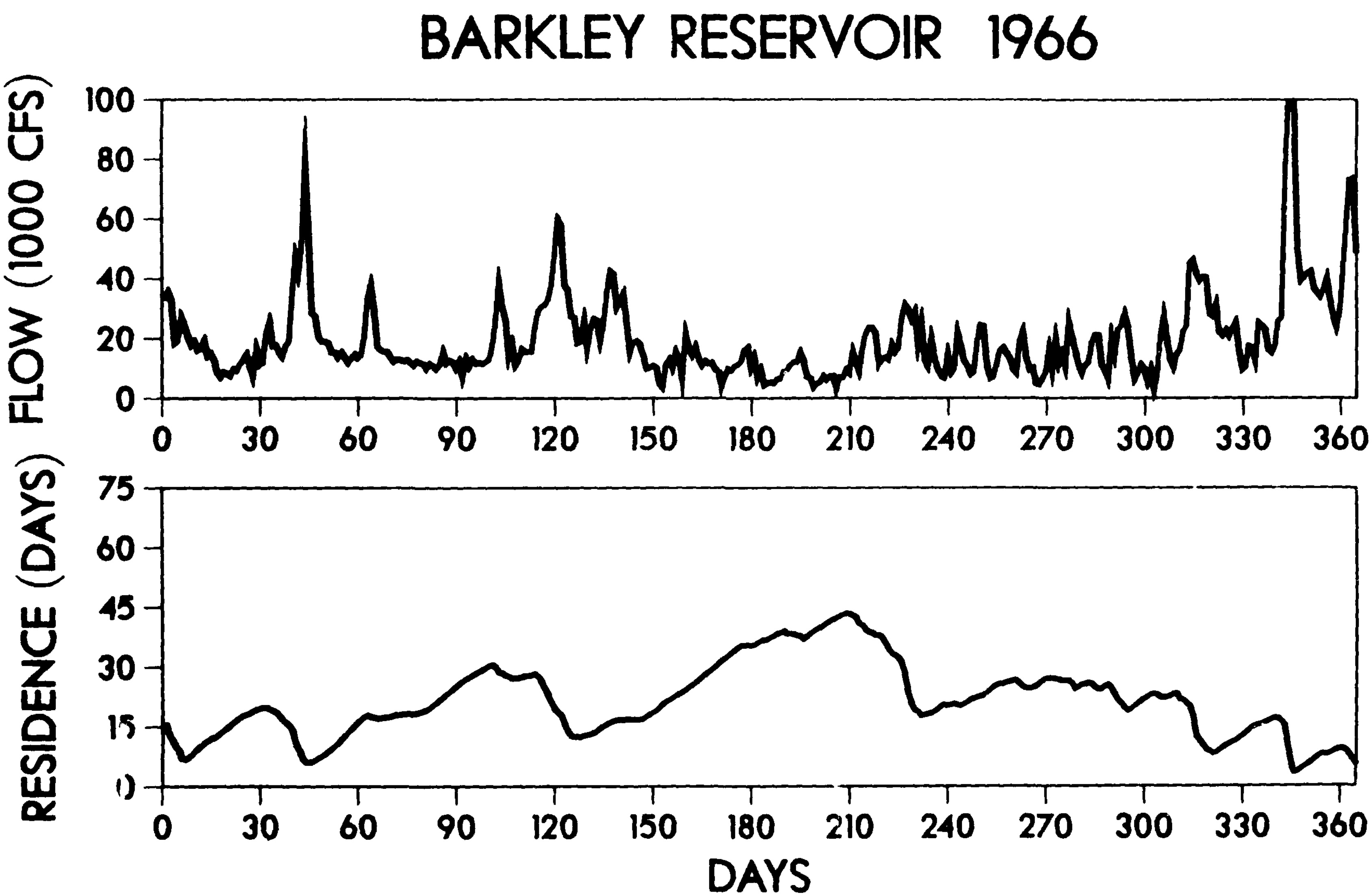
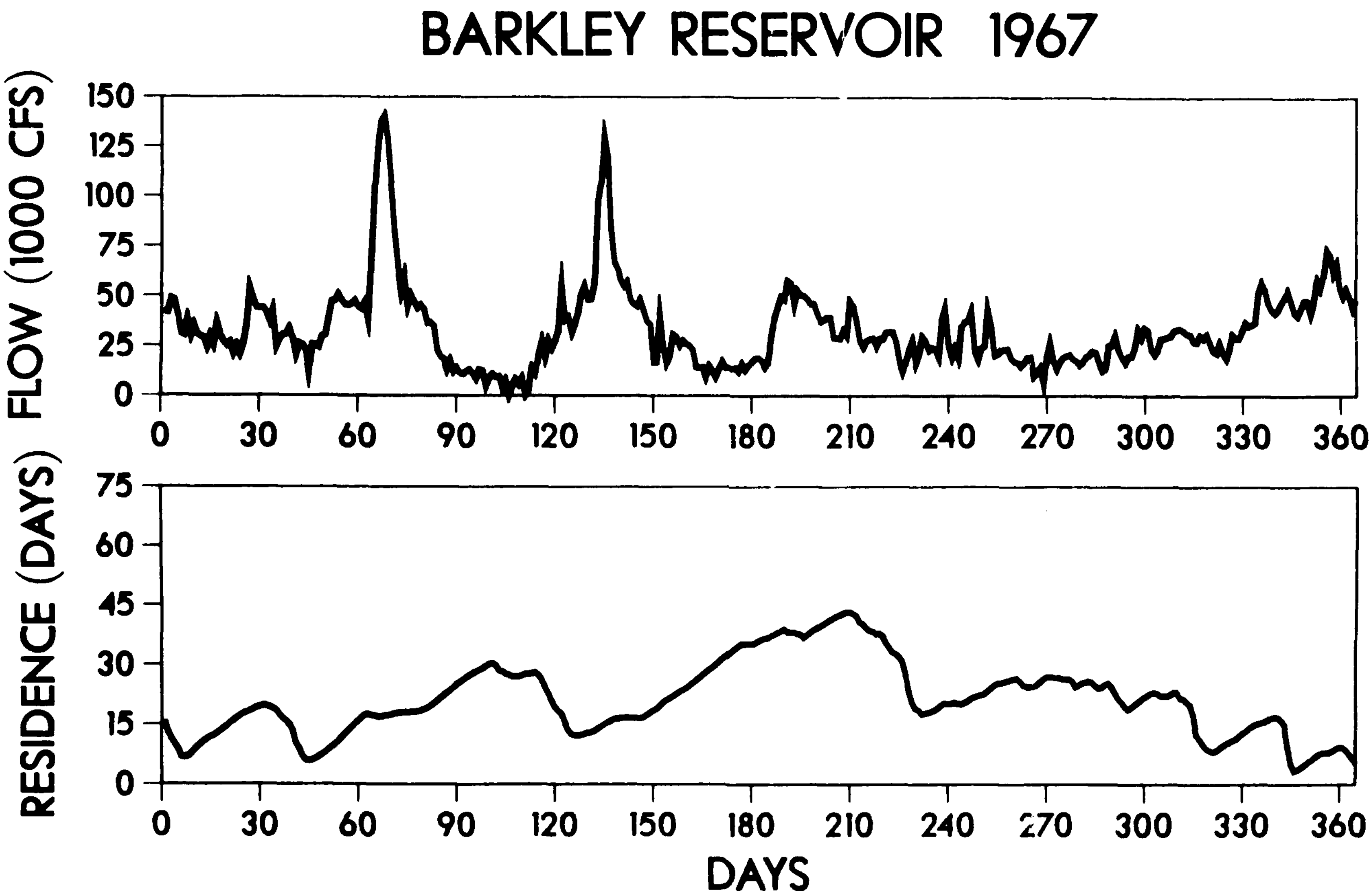


Figure 3 Barkley Lake Daily Flows and Residence Times for 1966-1987



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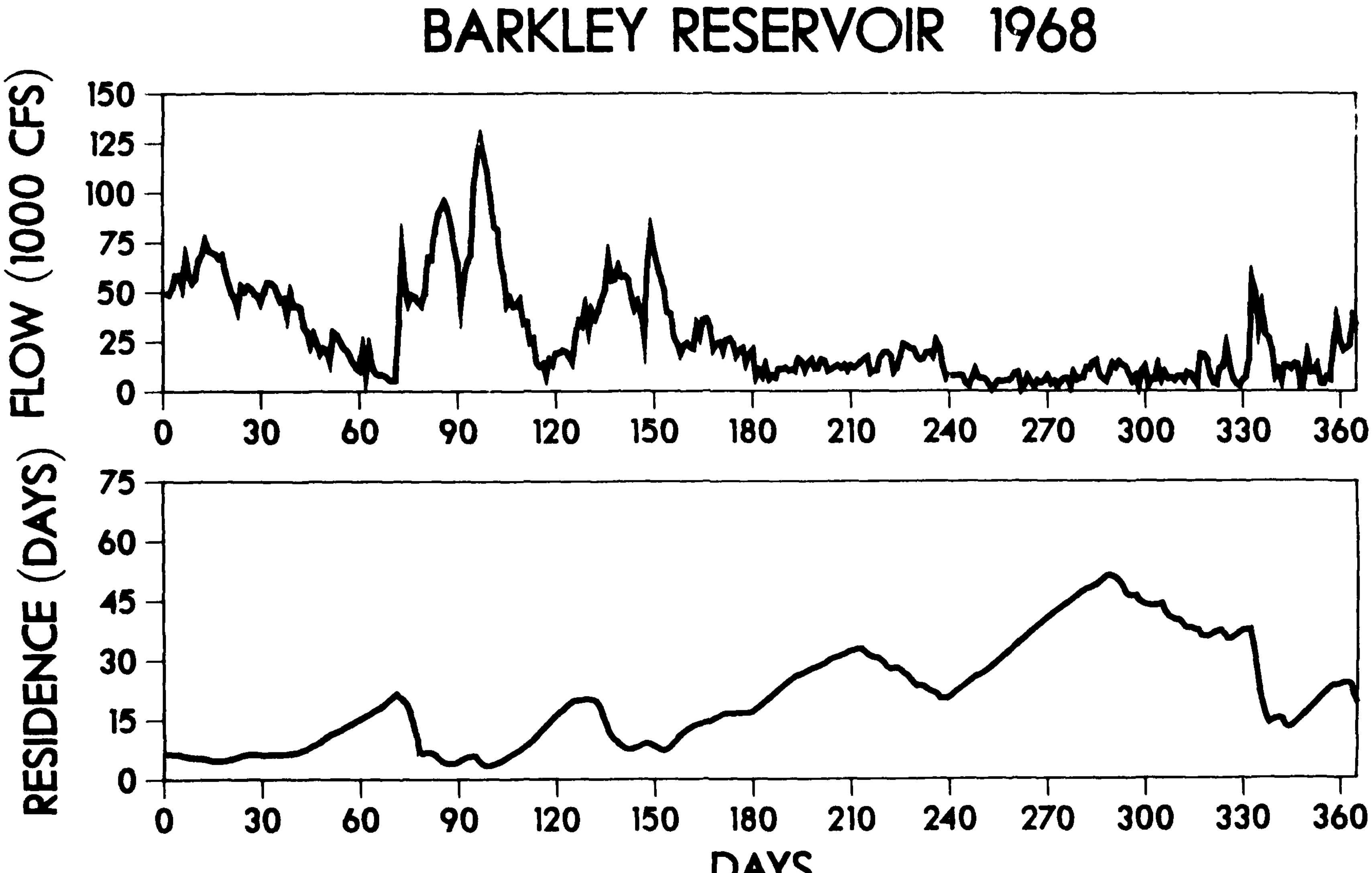

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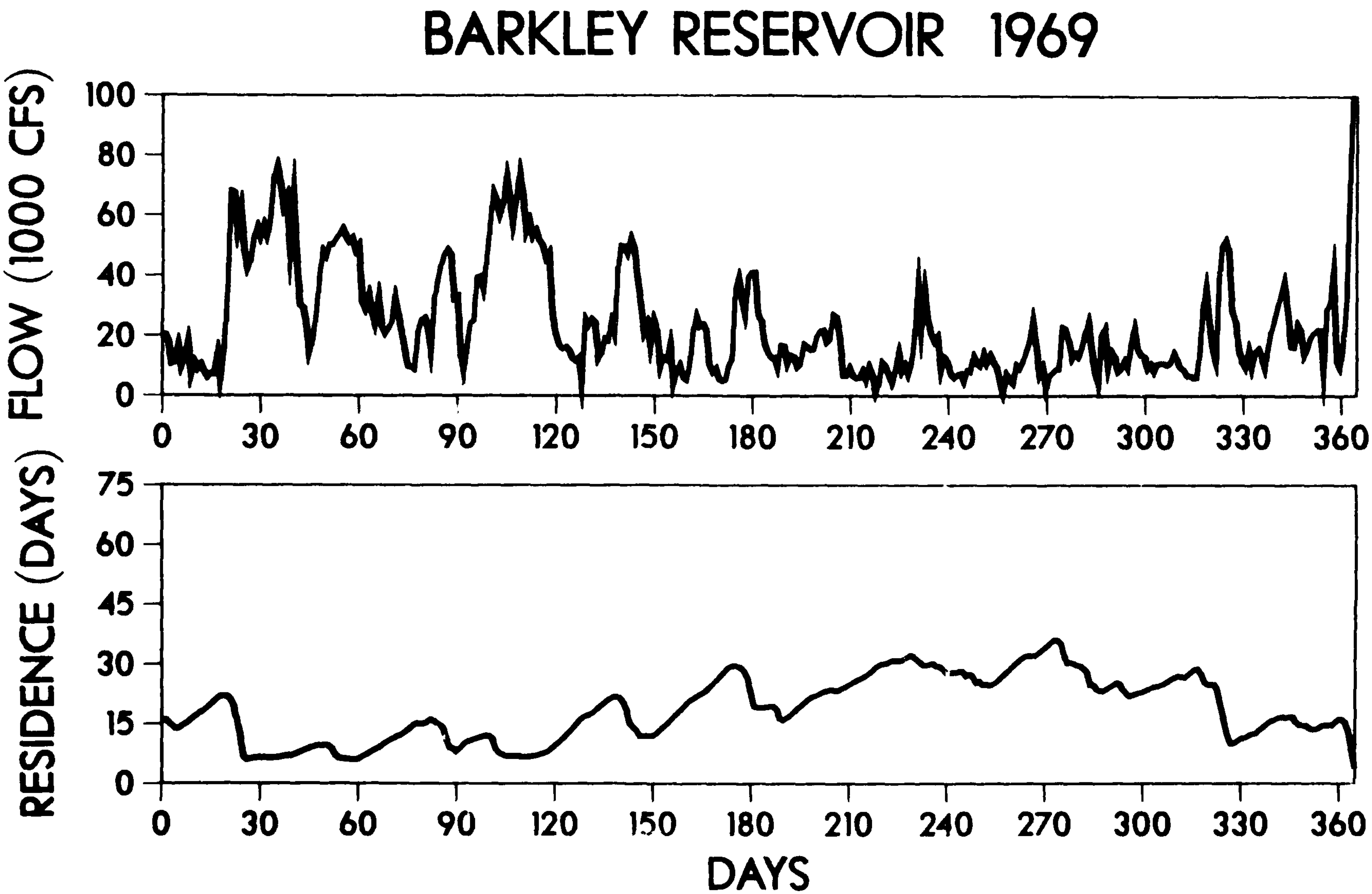

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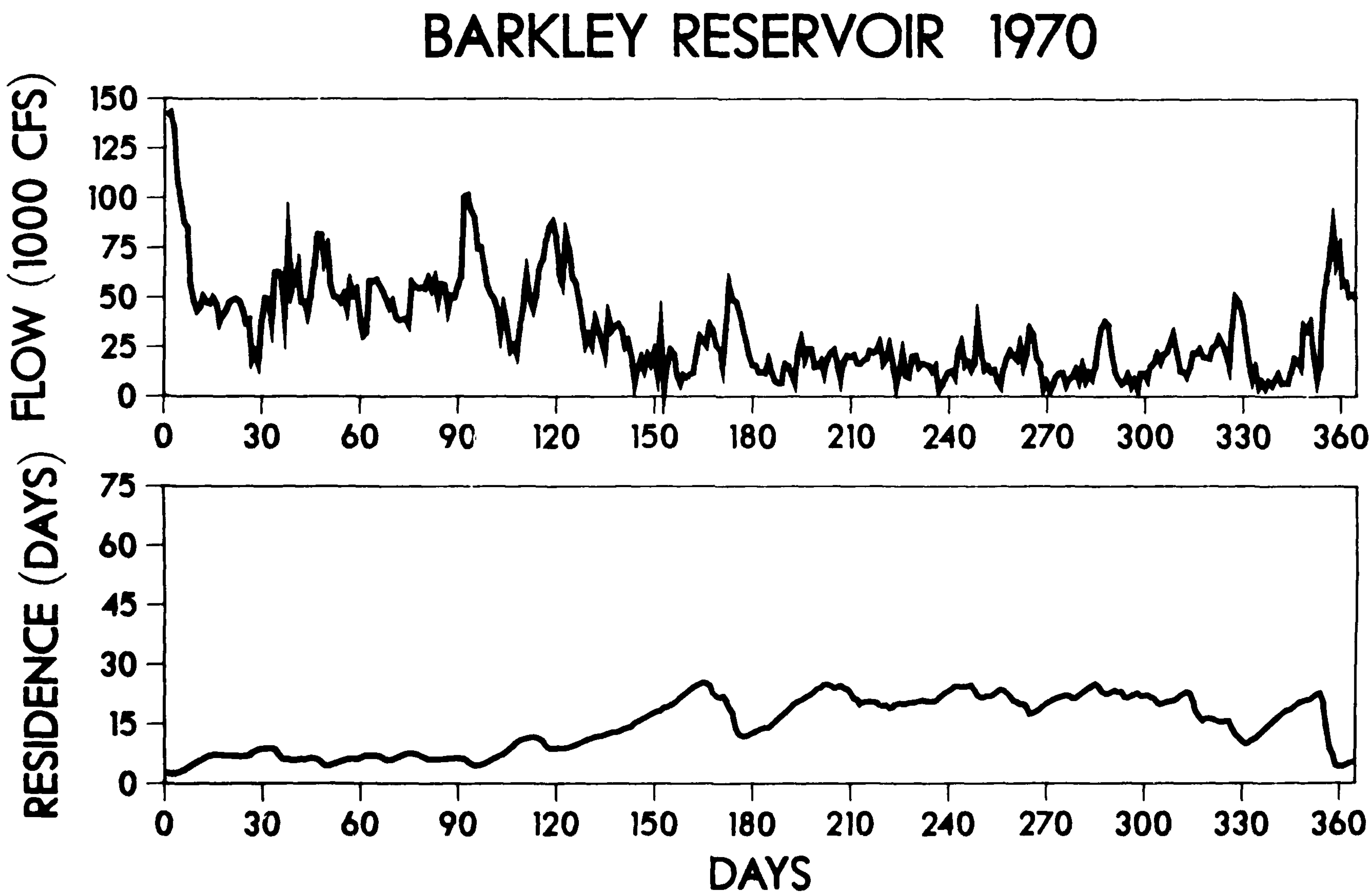

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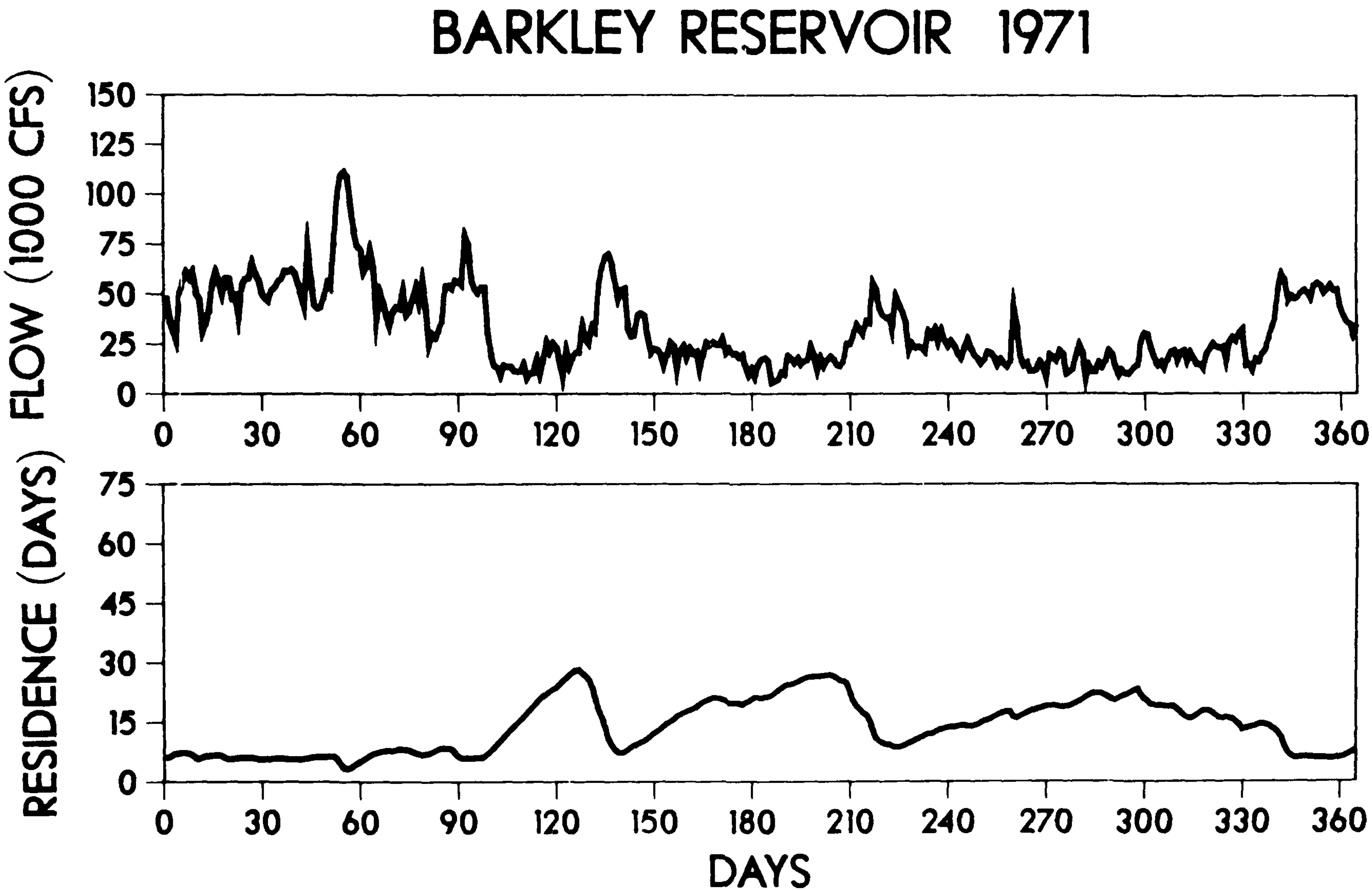

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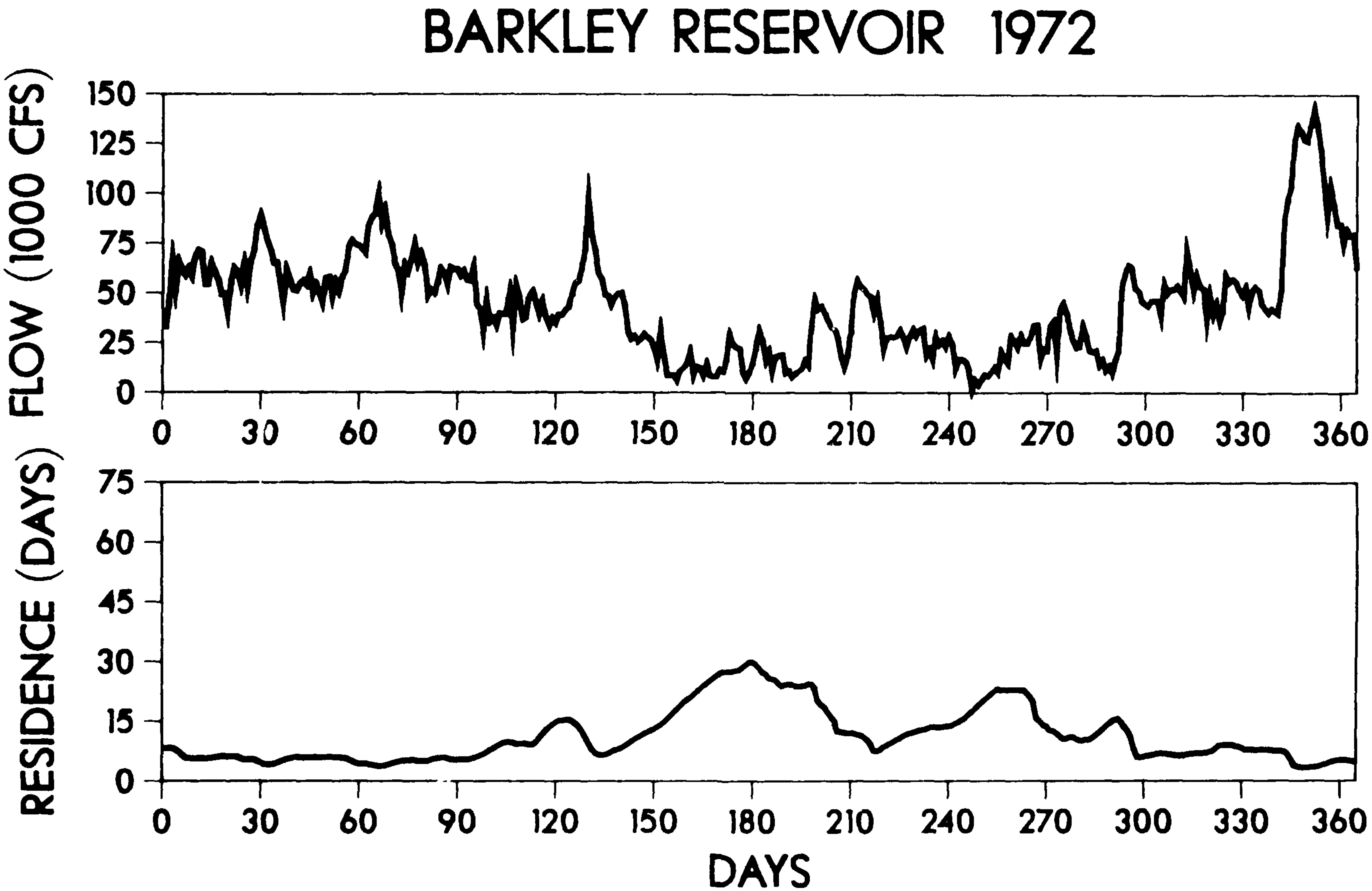

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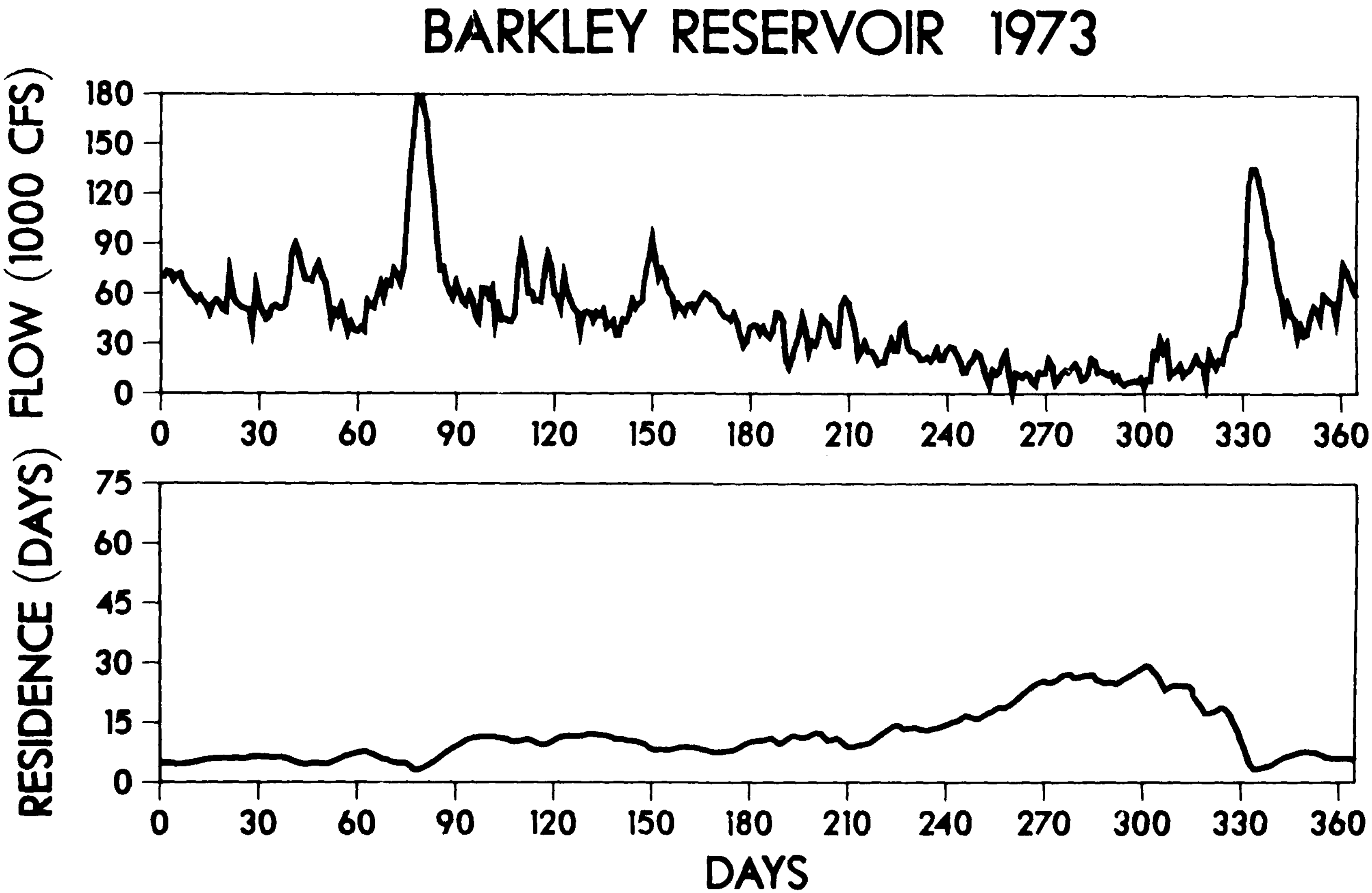

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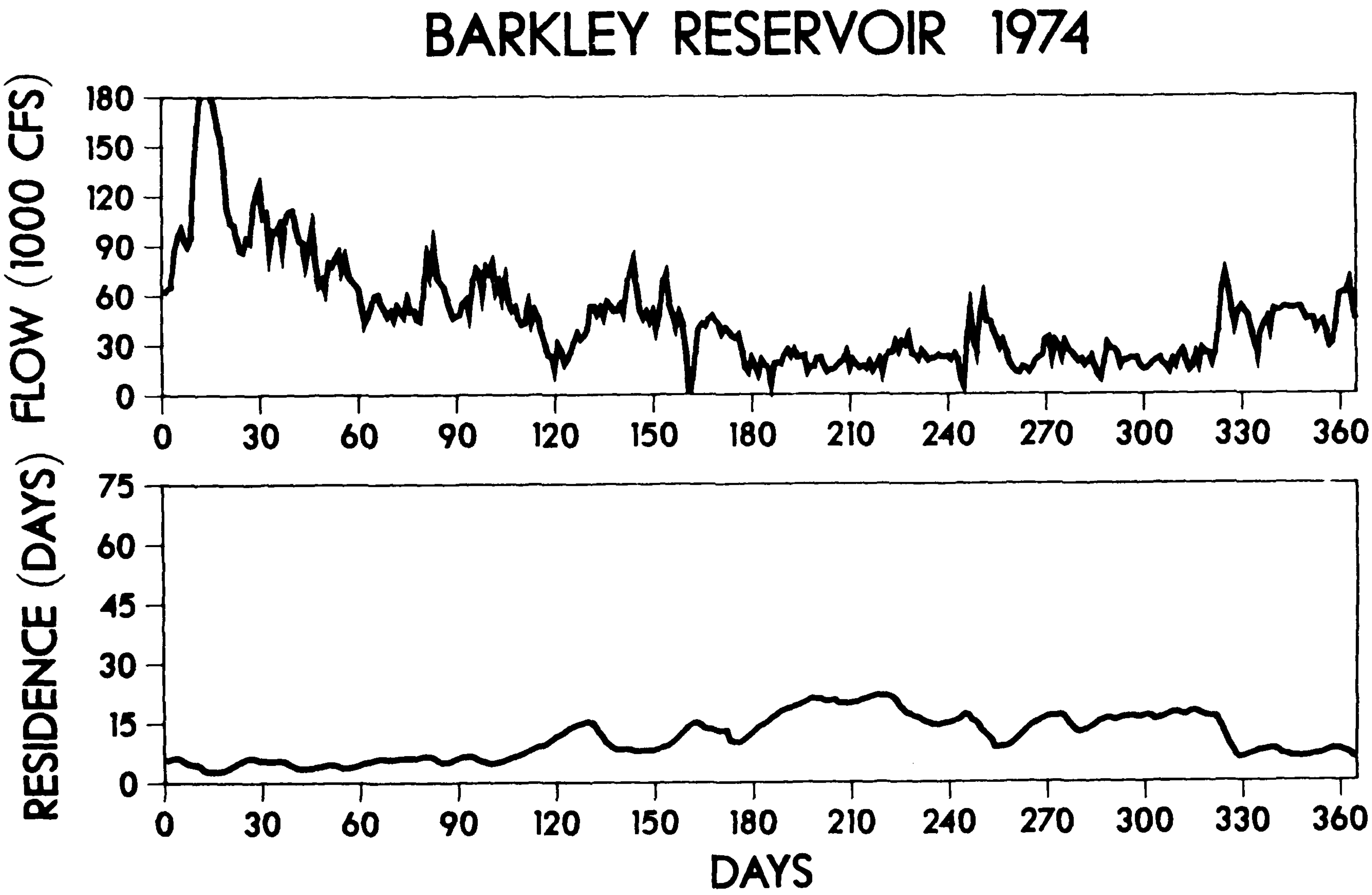

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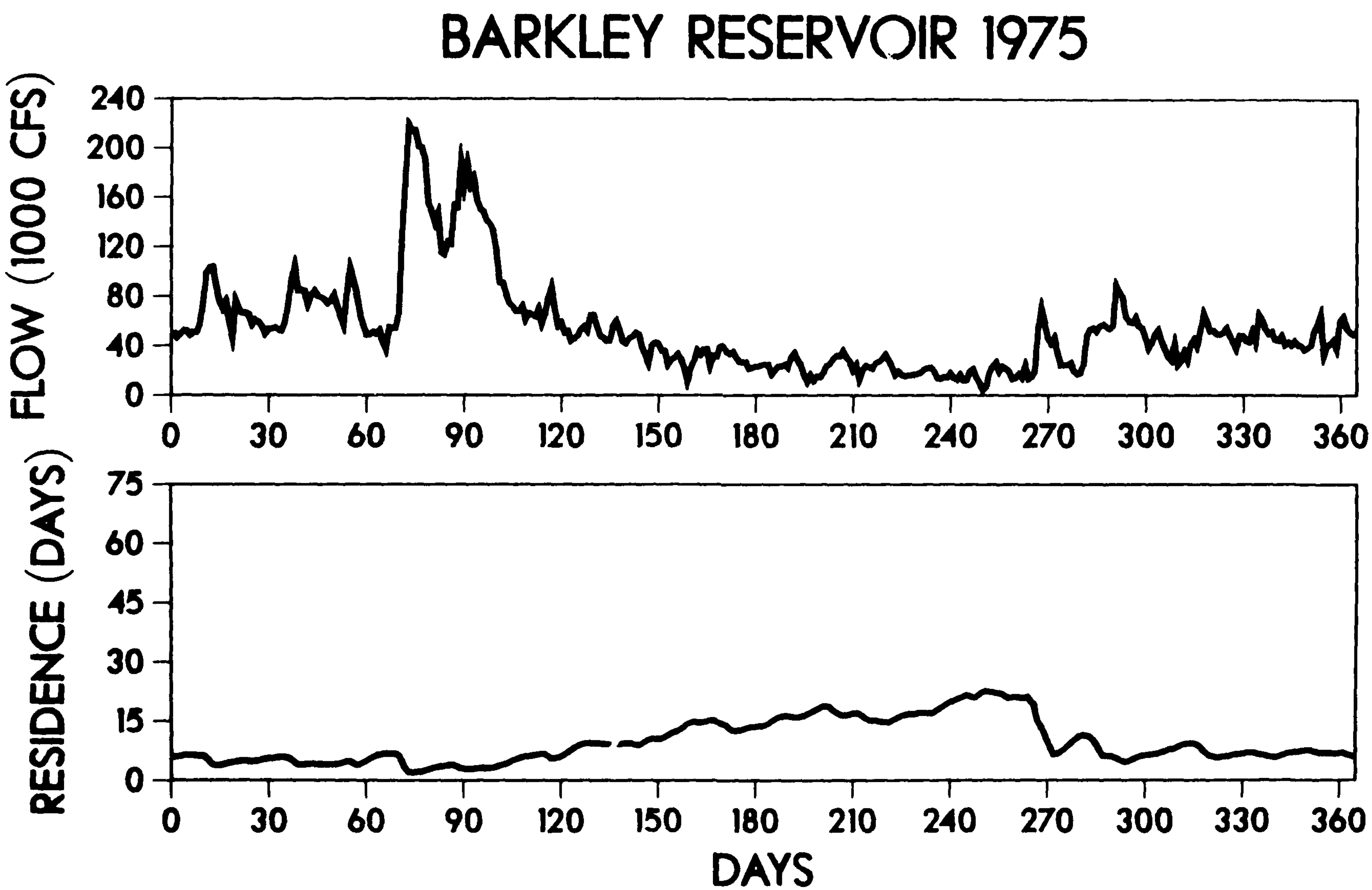

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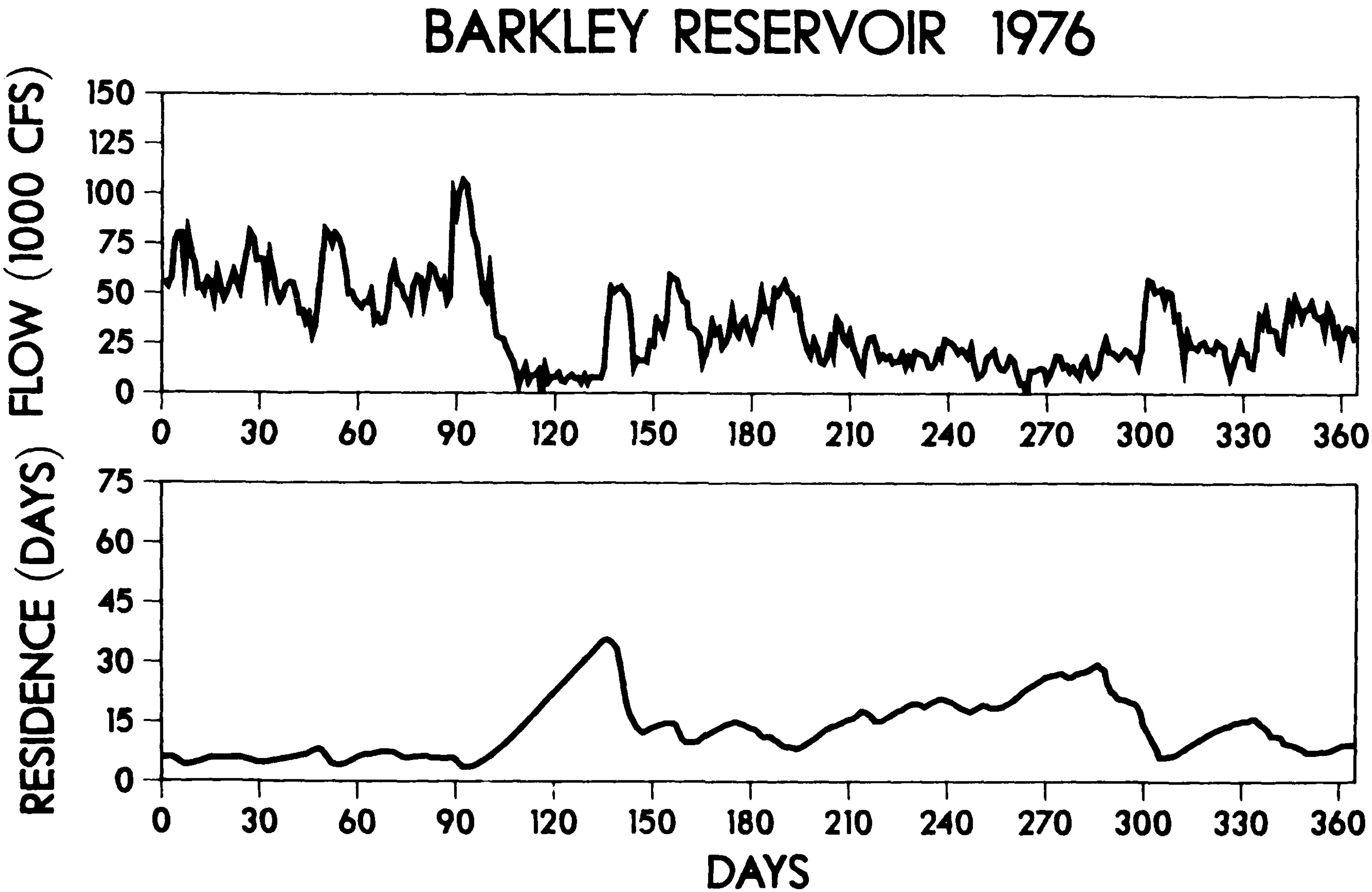

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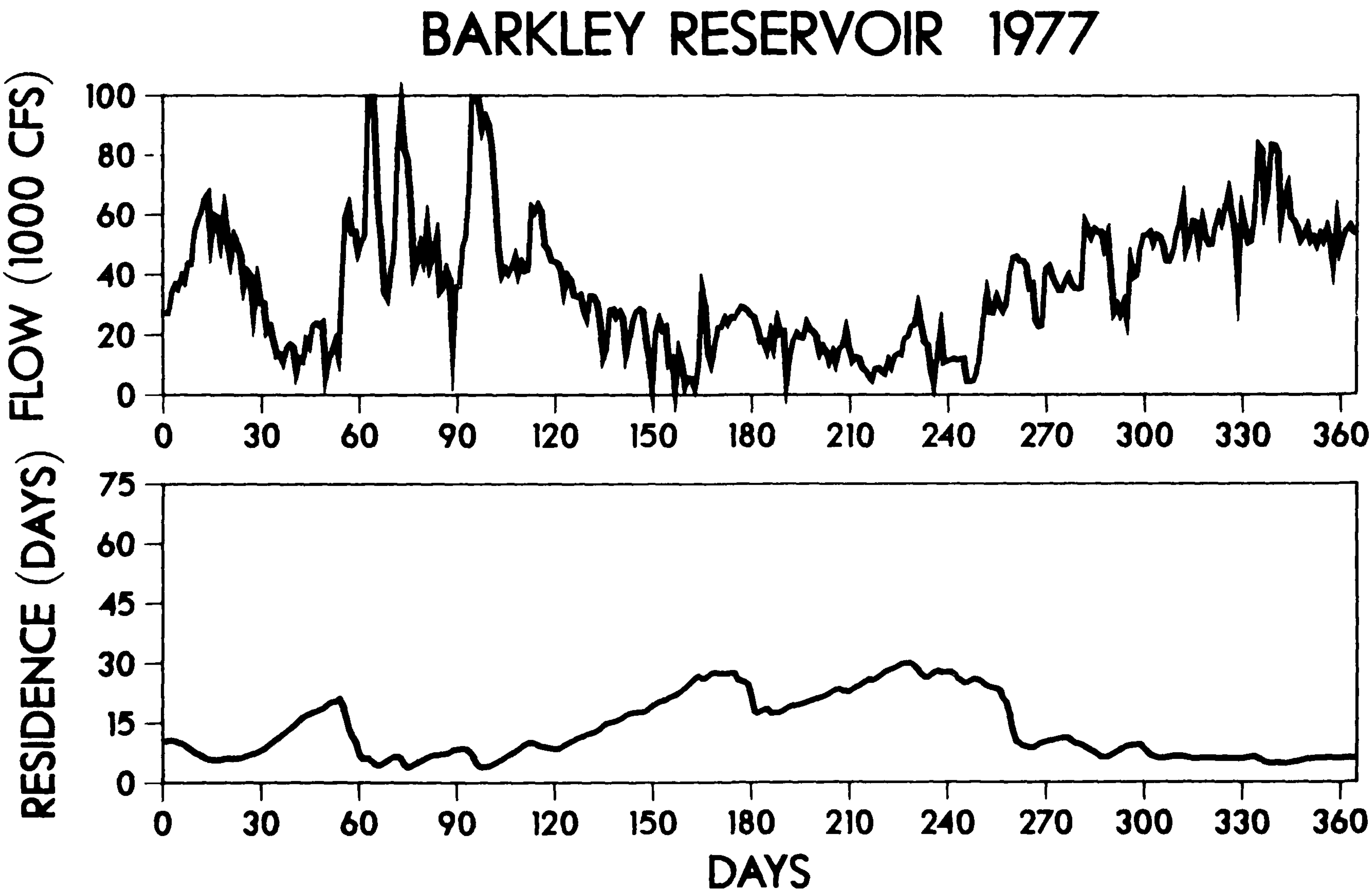

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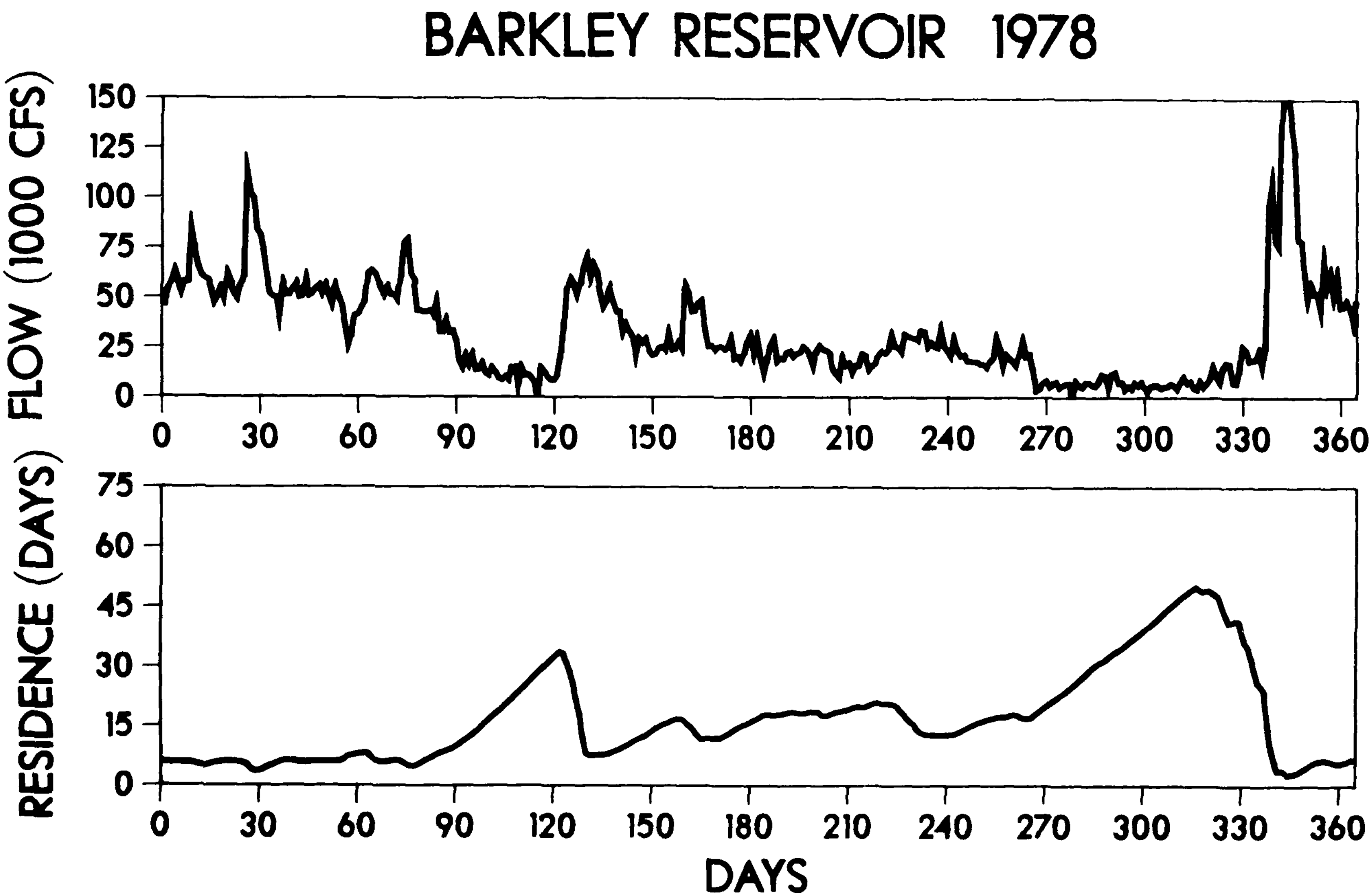

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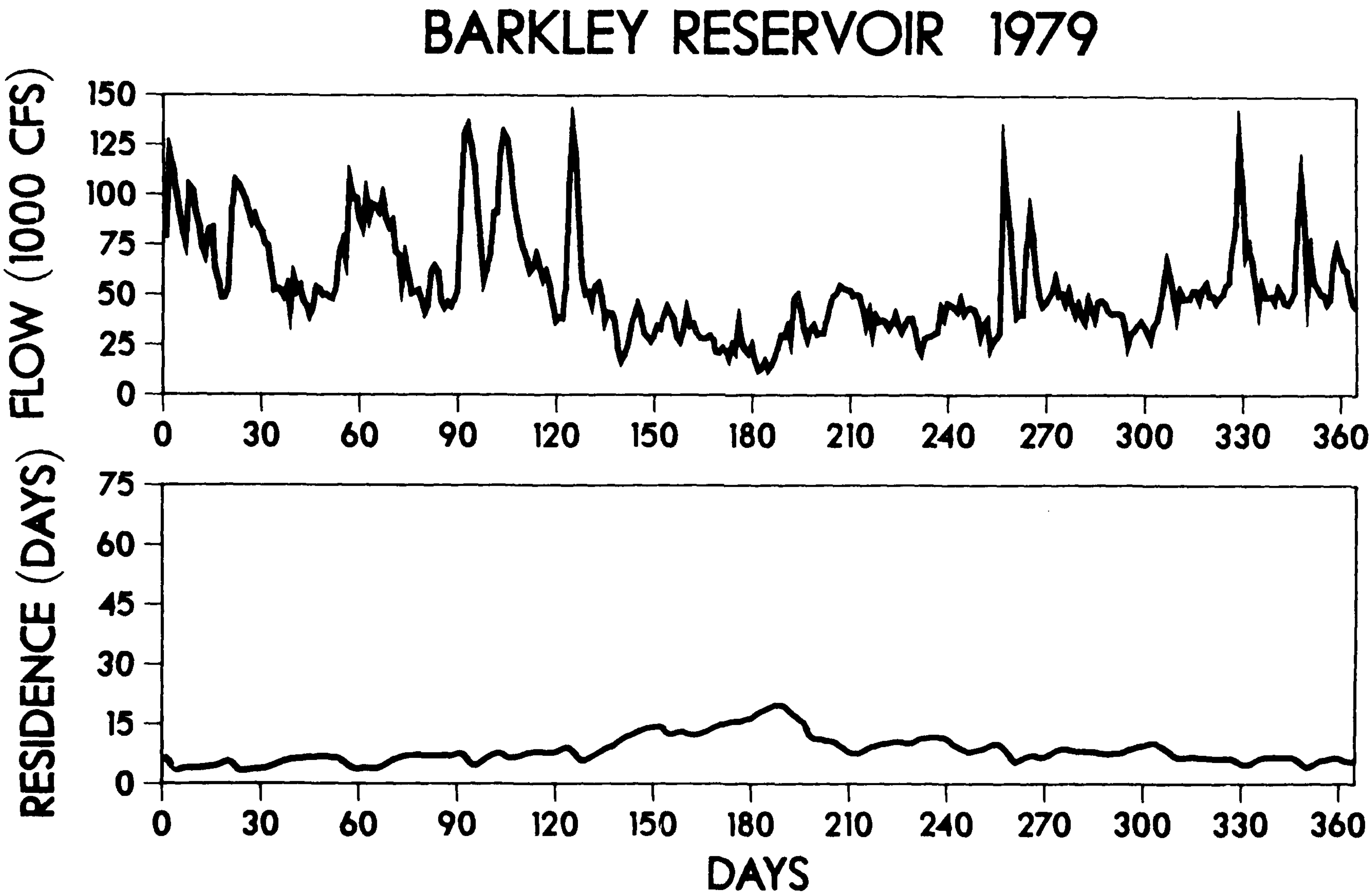

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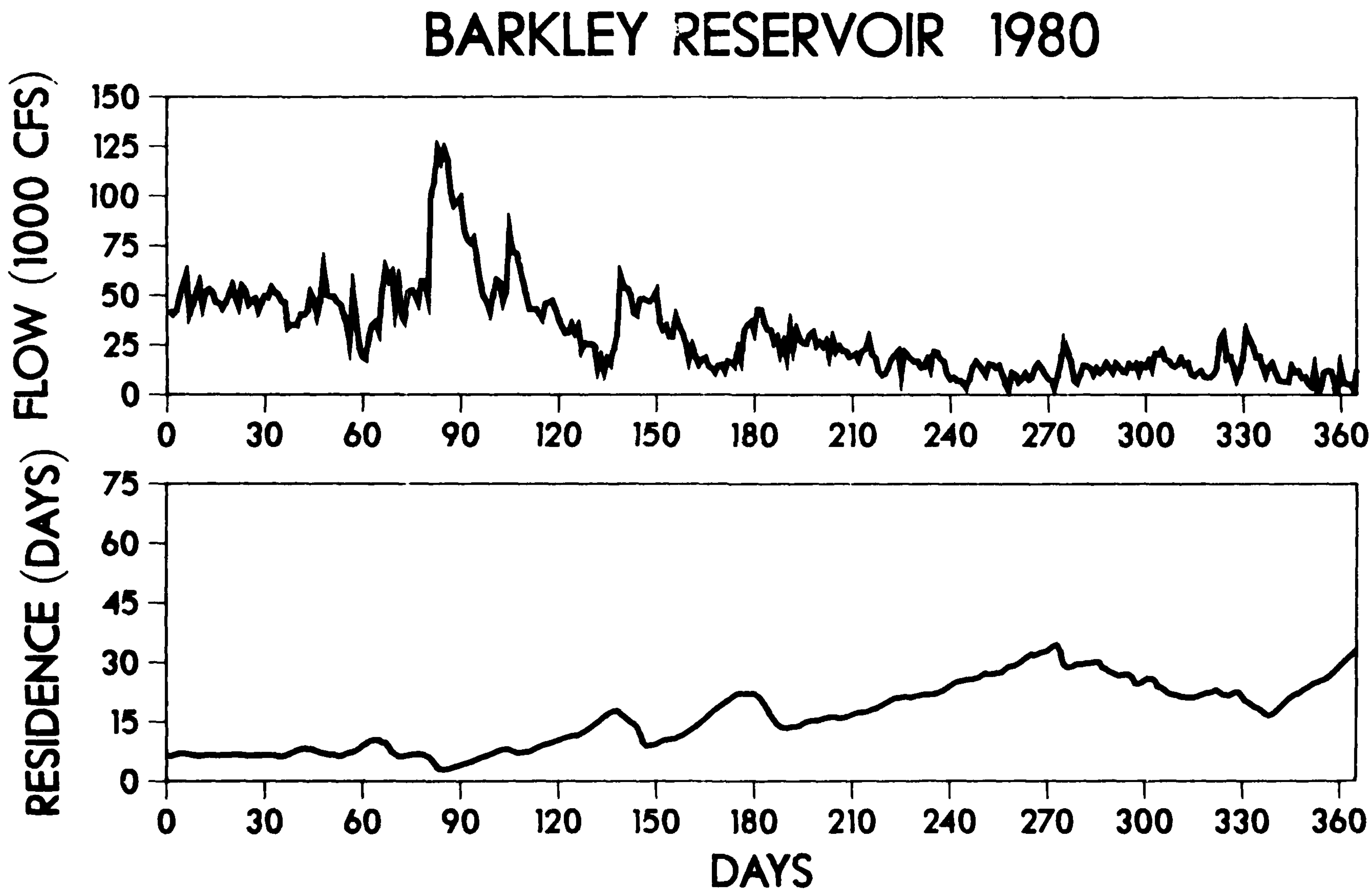

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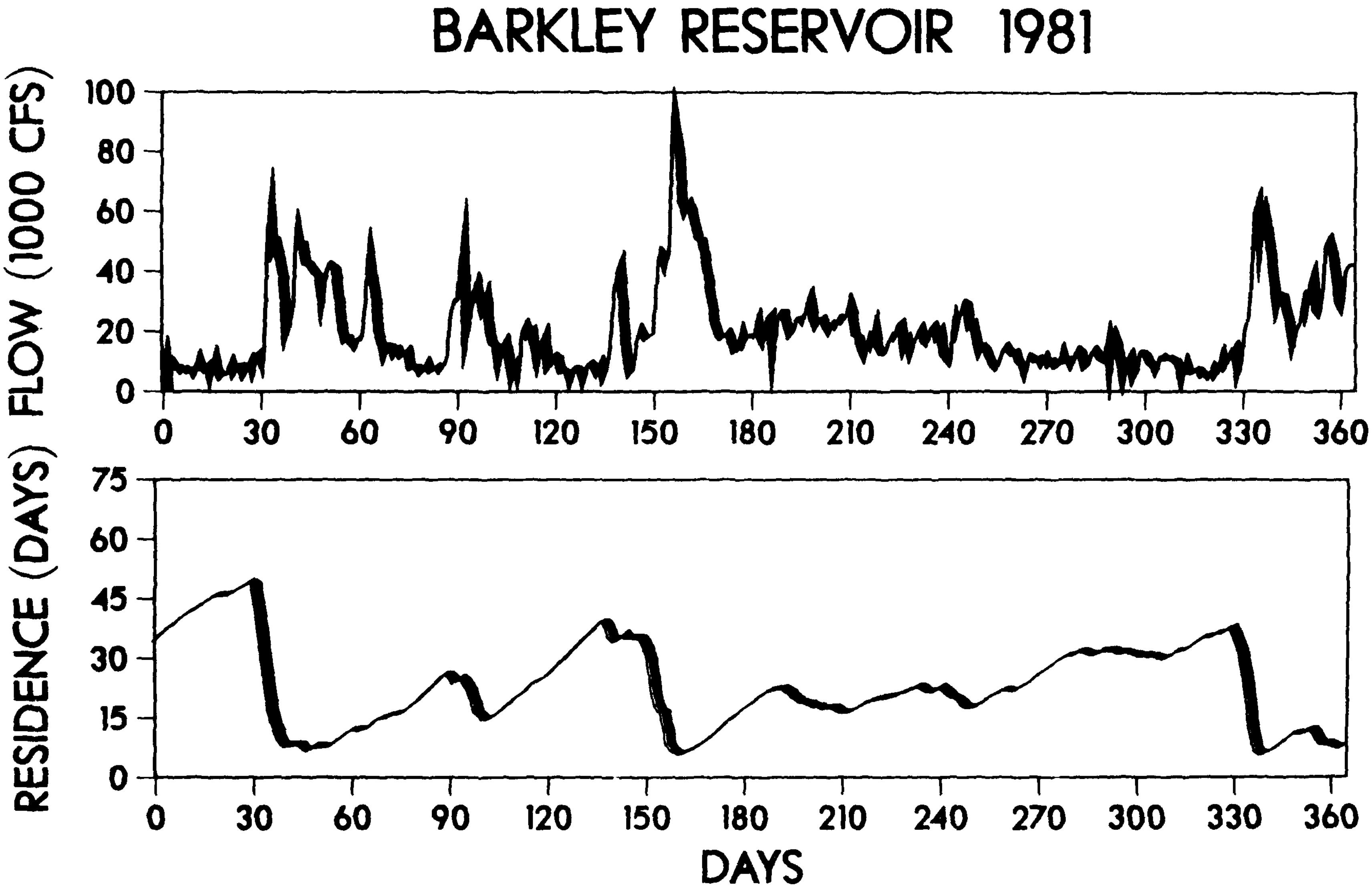

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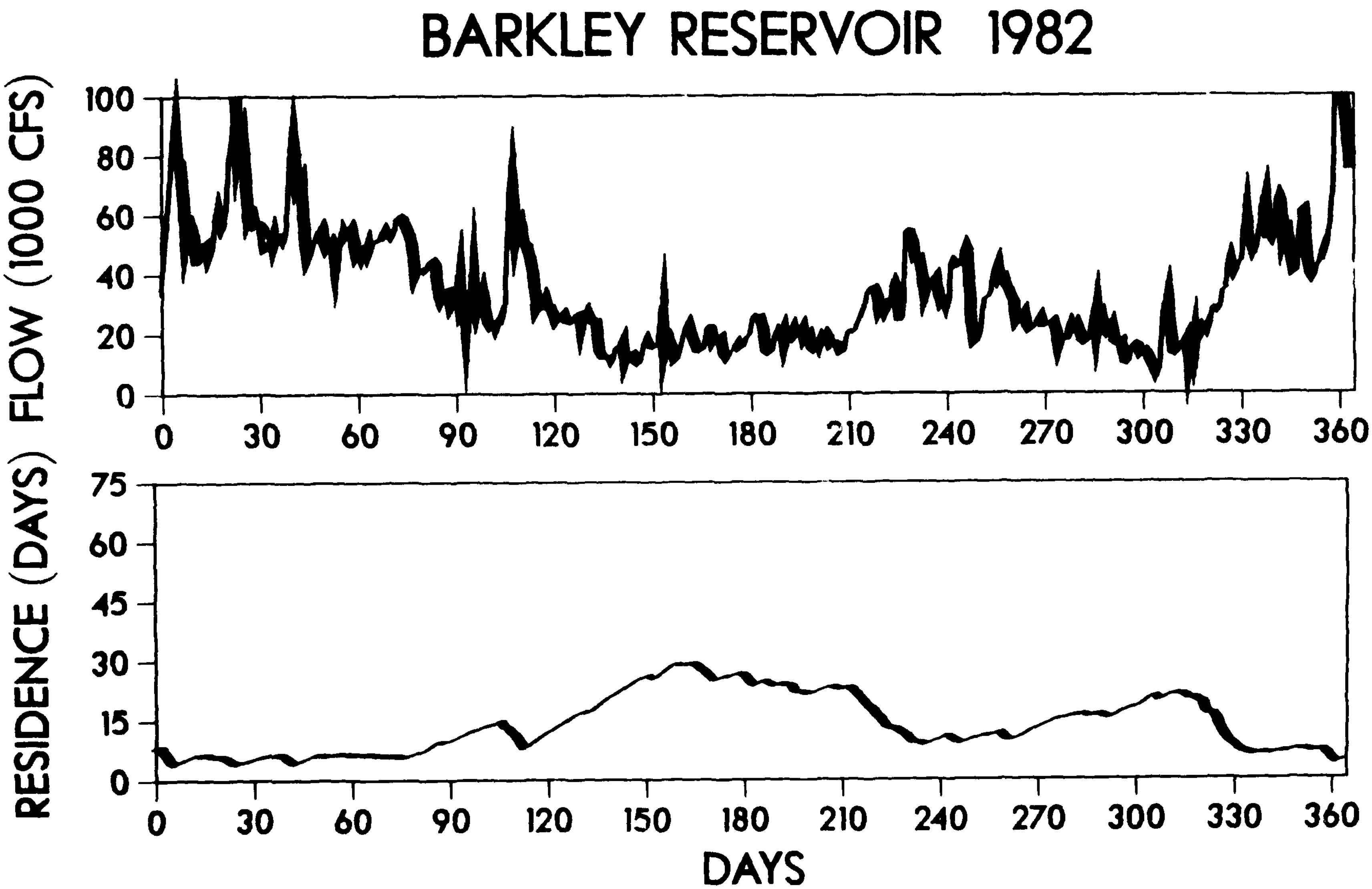

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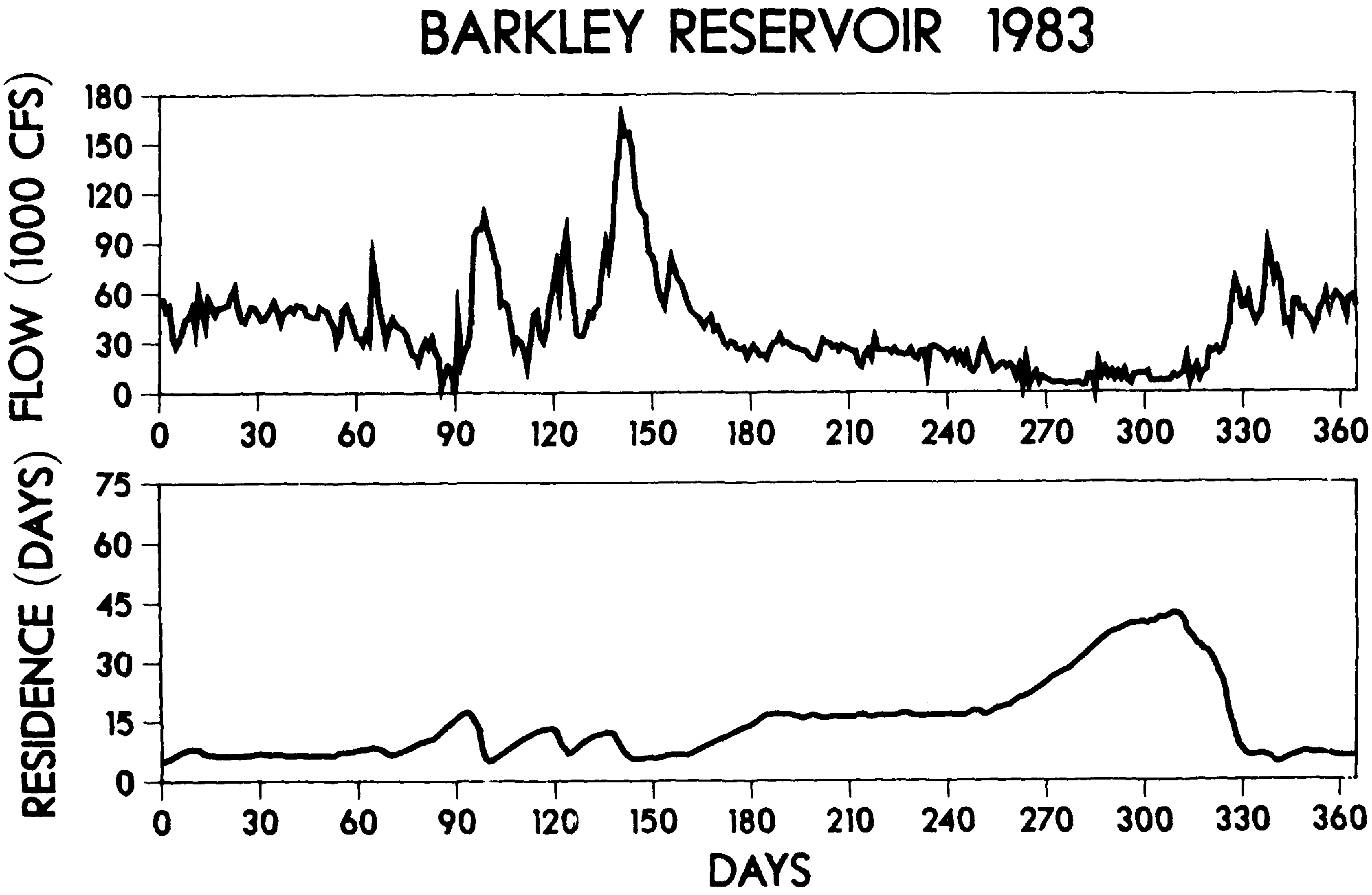

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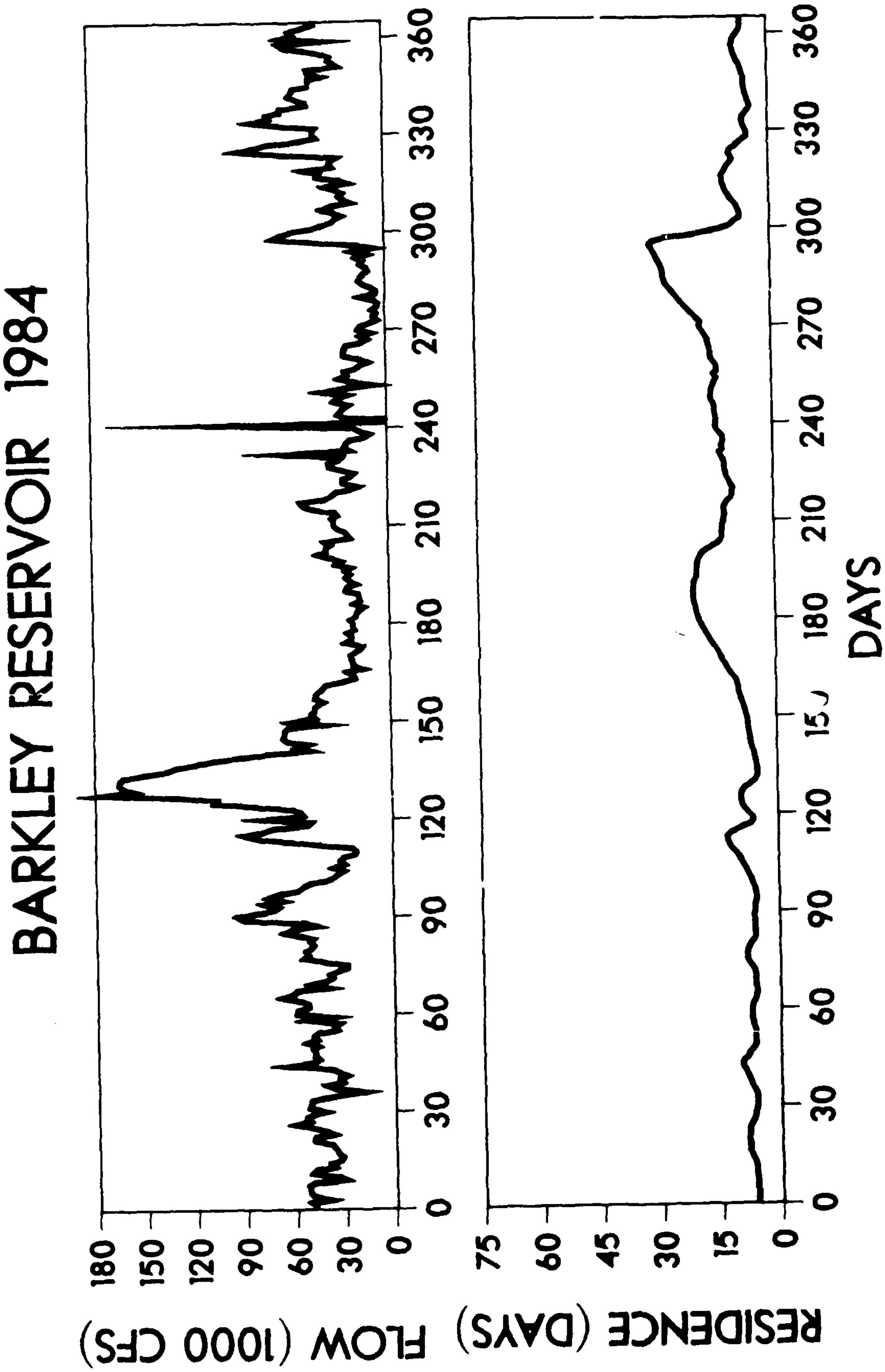

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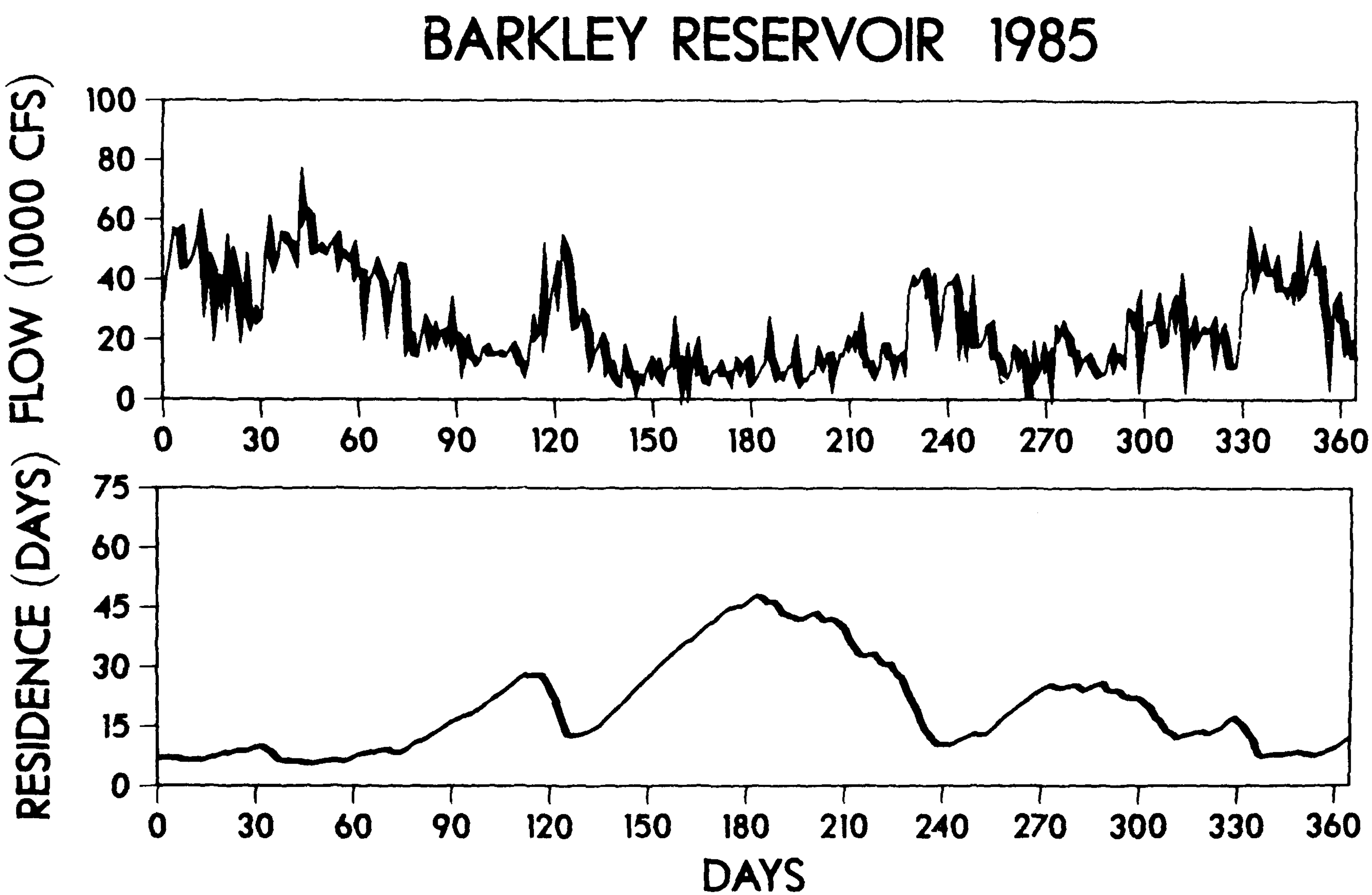

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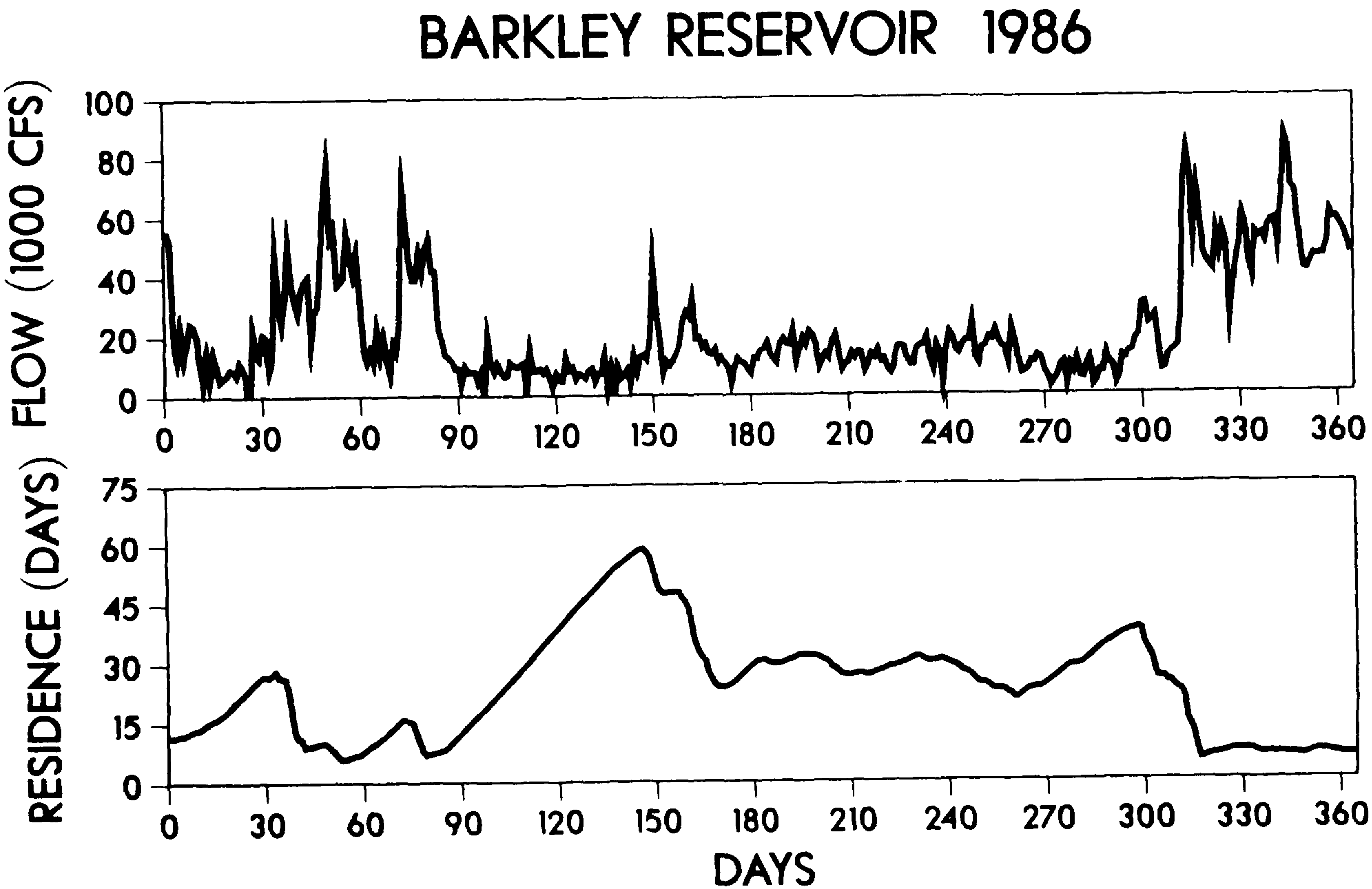

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BARKLEY RESERVOIR 1987

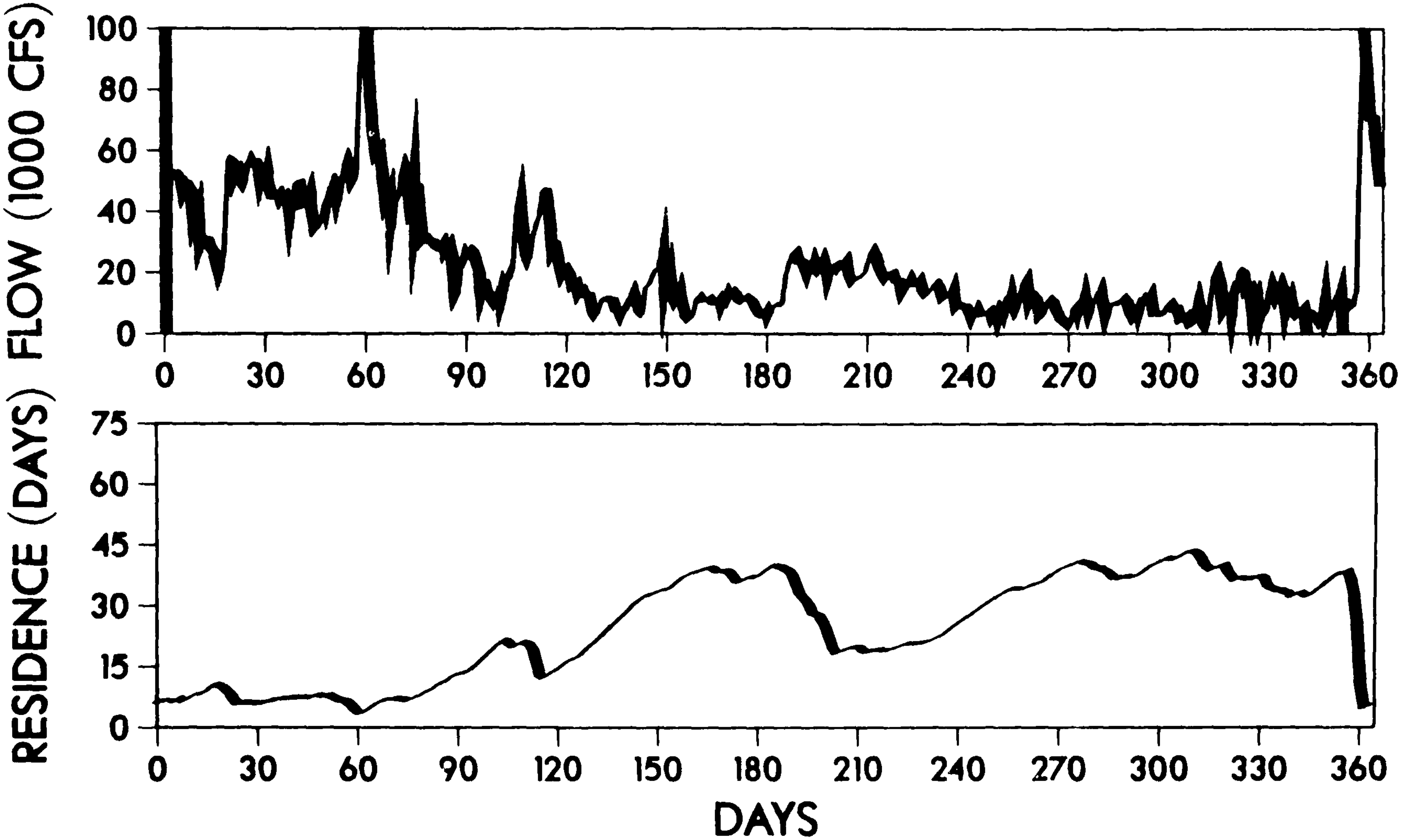


Figure 3 (continued)

of low flows that produced long residence times extending for a month or two. The years 1966, 1967, and 1968 each had extended periods with residence times greater than thirty days during the summer or fall. During 1978 there were two distinct low flow episodes causing long residence times in early May and again in November. Residence times during the stratified period of 1978 were about 20 days. The study year 1984 was representative of near normal flow conditions, with residence times of generally less than 20 days. By comparison, 1985 had very low flows and high residence times during the middle of the summer. Strong stratification and other water quality gradients were observed during this period. Flows were again unusually low during 1986, providing another good opportunity for observing and modeling extreme water quality changes in Lake Barkley.

APPLICATION OF BETTER MODEL TO BARKLEY LAKE

The BETTER model has been previously applied to Cheatham Lake (Brown et al., 1989) and Old Hickory Lake (Brown et al., 1986), which are the next two upstream reservoirs on the Cumberland River. A different 2-D water quality model (CE-QUAL-R2) was applied to Cordell Hull, which is the fourth mainstem reservoir on the Cumberland River (Howington, 1988). The study objectives for these previous model applications were similar to those being investigated for Lake Barkley in this report. The same general approach was taken, except that the capability of modeling embayment branches was added to the BETTER model. This capability already existed in the CE-QUAL-W2 model that was applied to Cordell Hull.

BETTER Model Description

The concept for the two-dimensional reservoir water quality model is quite simple. The reservoir volume is divided vertically and longitudin-¯ly into an array of volume elements. Daily inflow, outflow and inflow concentrations for parameters of interest are specified. Meteorological conditions govern warming and cooling at the surface. Important chemical and biological processes are simulated within the volume elements as water moves through the reservoir and mixes with adjoining volume elements. The resulting daily concentrations are calculated and displayed graphically.

Longitudinal segments are chosen to provide adequate resolution of observed or expected water quality patterns. Shallow surface layers and thicker layers near the bottom are usually specified. The model uses a floating layer scheme so that all calculated concentrations are at fixed depths from the water surface elevation. This allows direct comparison with field data.

Many important features of the flow field can be estimated based on the relative volumes, surface areas, and conveyance areas of the model elements. The calculated flows through the segment volumes determine the residence time patterns. The conveyance areas and the calculated flows determine the velocity patterns.

Sediment oxygen demand (SOD) as well as surface reaeration and heat exchange involve surface areas. The air-water interface area is the surface area of the top layer of segments. The sediment area of the bottom layer is equal to the surface area of that layer. Sediment areas of intermediate layers is the difference between the top surface area and the bottom surface area.

Each inflow is simulated as though no other inflows or releases were being made. The longitudinal distribution of flow is proportional to the downstream

surface area, so that a flat pool is maintained. This longitudinal inflow distribution is then partitioned vertically according to the conveyance areas of the segments within each column, resulting in a uniform velocity distribution.

During stratified conditions, inflows move toward layers with matching density. This is accomplished by finding the matched density point in the downstream water column, assuming a linear density gradient between downstream layers. The element flow is deflected vertically in proportion to the downstream matched density point. This same fraction of flow is deflected from all downstream segments within the layer.

Downstream momentum may be large enough to override these density deflections. This is modeled by limiting the vertical density deflections for large densimetric Froude numbers. A horizontal densimetric Froude number is calculated for each segment as:

$$F_D^2 = \frac{U^2}{\Delta\rho/\rho g H}$$

Where

U = downstream velocity (ft/sec)

$\Delta\rho/\rho$ = relative longitudinal density difference

g = gravitational acceleration (ft/sec^2)

H = layer depth (ft).

At larger Froude numbers the momentum overwhelms buoyancy, while at small Froude numbers density differences dominate. The vertical deflections are limited once the densimetric Froude number is greater than 1.0 as:

$$\text{Actual deflection} = 1/F_D^2 \cdot \text{matched density deflection.}$$

Vertical flows resulting from these deflected inflows are calculated by mass balance for each segment.

The outflow distribution at each outflow column is determined by estimating the vertical withdrawal zone for the outlet. The model assumes that the vertical extent of the withdrawal zone depends primarily on the total outflow rate and uses a truncated triangular distribution. The outflow zone above and below the outlet is calculated as:

$$\text{Withdrawal Zone} = QTH \cdot Q^{.5} \text{ (ft)}$$

Where Q = outflow from outlet (cfs).

QTH = outflow coefficient (estimated as 1.0)

The outflow zone is truncated at the bottom and surface for large outflows leading to an almost uniform outflow distribution. When a vertical density gradient is encountered, the withdrawal velocity profile is limited beyond the density interface. The modeled limitation factor is a direct multiple of the layer densimetric Froude number:

Zone Limit = Minimum (Densimetric Froude * WDENS, 1.0) where WDENS is a calibration factor.

The vertical flow across the upper interface of each layer equals the withdrawals from below that interface. The total vertical flow is distributed in proportion to the upper interface area of each segment in the layer. Horizontal flows are then found by mass balance. The separately calculated inflow and outflow distributions are added together to estimate the net flows within the reservoir each day.

Three mechanisms causing vertical mixing between layers are simulated. These are convective mixing due to surface cooling, wind mixing, and turbulent mixing from the advective flows.

Surface cooling regularly occurs at night, but the model considers only daily average meteorology, so this dirunal cooling and mixing is not simulated.

Surface cooling occurs following storm front passage, and is the major mechanism causing late summer and fall mixing. Underlying layers are mixed with the surface layer until a stable density gradient is established or the bottom is reached.

Wind mixing is modeled as a balance between the kinetic energy from the wind stress and the potential energy of stratification. The wind energy available for mixing is modeled as 5 percent of the kinetic energy acting at the water surface, which is proportional to windspeed cubed. The potential energy represented by the existing density gradient between two layers is equal to the work required to lift the lower layer up to the center of the new mixed layer. The model iteratively mixes segments until the kinetic energy is fully used or the bottom of the column is reached. Regions of the reservoir with relatively large surface area are more strongly influenced by these surface mixing mechanisms.

The third mixing mechanism is turbulent vertical mixing from advective flows. A vertical exchange velocity between adjacent segments is estimated as a percentage of the downstream velocity.

Vertical density gradients act to suppress this turbulent mixing. A vertical densimetric Froude number is used to limit the degree of vertical turbulent mixing. The vertical exchange velocity is calculated as:

$$\text{Exchange Velocity} = C_{mix} \cdot F_D \cdot \text{Downstream Velocity}$$

$$\text{Where } F_D = \frac{U}{(\Delta\rho/\rho g H)^{1/2}}$$

With U = velocity of upper layer

$\Delta\rho/\rho$ = relative vertical density difference

H = lower layer depth

C_{mix} = vertical mixing coefficient.

The daily exchange rate is calculated from this velocity estimate.

Once the reservoir flow and mixing patterns are determined, a heat balance is used to calculate a new temperature distribution. A mass balance, using these flow and exchange rates together with internal sources and sinks, is used to estimate new concentrations of each modeled variable.

Reservoir temperatures are calculated from surface heat exchanges and the adsorption of solar radiation. Solar radiation is assumed to be 50 percent infrared and ultraviolet, which is adsorbed very near the surface and included as a surface heat exchange term. The remaining 50 percent is visible light and penetrates exponentially as:

$$I(Z) = I_o \exp(-kz)$$

where I_o = radiation directly below surface (50 percent measured)

k = light extinction coefficient, m^{-1}

z = depth (m).

The light extinction coefficient is a function of suspended materials in the water. The model considers suspended sediment and algae as the major contributors to light extinction, beyond the background extinction of 1.0 m^{-1}.

$$K = 1.0 + .10 * SS + .10 * Algae$$

where Algae = dry weight algae biomass (mg/L)

SS = suspended solids (mg/L)

For the background extinction of 1.0 m^{-1}, the one percent light level is about 15 feet.

Water temperatures for each surface segment are used to estimate the net heat transfer by calculating individual heat transfer terms for using daily average dry bulb, dewpoint, windspeed, and solar radiation data. Heat transfer

terms include long wave radiation between the air and water surface, and wind driven evaporative and convective exchanges.

Dissolved oxygen patterns are modeled by considering the sources and sinks acting in the reservoir together with the inflow of oxygen and oxygen consuming organic materials. These various sources and sinks for dissolved oxygen must be modeled correctly throughout the reservoir during the simulation period to accurately reproduce the observed DO patterns.

The model considers the traditional variable, 5-day BOD, to be composed of two separate quantities; dissolved organic materials, and detritus. The difference is that detritus slowly settles within the reservoir (0.1 m/day) and decays at a slower rate (0.0375 day^{-1}) than dissolved organics (0.075 day^{-1}). Both of these materials enter with the inflow or waste discharge loads and consume oxygen as they decay.

The oxidation of 1 mg/L NH_3-N to NO_3-N requires approximately 4.7 mg/L of oxygen. Ammonia enters the reservoir in the inflow, and in waste discharges. Ammonia is released during algae respiration and detritus decay. The rate of oxidation and decay increases with temperature.

Sediment oxygen demand (SOD) is modeled as an areal demand that increases with temperature, but does not otherwise change. The model allows the SOD rate to be specified for each longitudinal segment. The SOD affects the dissolved oxygen most dramatically in bottom elements during stratified conditions.

The model does not consider respiration of benthic organisms, nor are fish, zooplankton, or aquatic weed respiration included as oxygen sinks. The only other modeled oxygen sink is respiration of algae.

Photosynthetic production of oxygen depends on the distribution of algae biomass and the algae growth rate, which may be limited by nutrient availability

and the vertical profile of light. For each 1 mg/L of algae growth, 1.6 mg/L of dissolved oxygen is produced. The respiration of 1 mg/L algae requires 1.6 mg/L oxygen. But the unequal distribution of these oxygen sources and sinks can lead to surface supersaturation and metalimnetic depletion of oxygen concentrations

Surface reaeration is the final modeled process influencing oxygen concentrations. Oxygen transfer is modeled as a function of windspeed, advective flow velocity and dissolved oxygen deficit (or excess) from saturation. Intense algae growth can easily produce supersaturated DO concentrations, but surface exchange will cause the DO to decrease towards saturation.

Several additional water quality variables are simulated to provide the basis for estimating algal growth and biomass levels. Algae growth is modeled as a function of temperature, light level, and nutrient concentrations (N, P, and C).

Suspended solids are modeled to provide estimates of the light attenuation due to inorganic substances, in addition to light adsorption by the algae itself. Suspended solids are assumed to settle at a constant rate of 0.5 m/day. The model considers 50 percent of the total solar radiation to be photosynthetically active radiation (PAR), so the light extinction profile used in the heat balance computations is also used to estimate available light for algae growth. High suspended solids or high algae concentrations will limit the light penetration and restrict the euphotic zone to near surface layers. When the euphotic zone (1 percent PAR) is less than the surface mixed layer, half the average light level is used, to account for limited light exposure of mixing algae. Algae growth is governed by a half-saturation curve for light (without inhibition at high light).

Nitrogen is available as either NO_3-N or NH_3-N without preference. Nitrogen limits growth when the demands for algae growth exceeds the supply, including the release of nitrogen (NH_3) during respiration. Nitrogen is assumed to be 6 percent of algae biomass by weight. Phosphorous is assumed to be 0.4 percent algae biomass and limits algae growth if the requirement exceeds the available phosphorous supply, including that being recycled during algae respiration. No sinks for phosphorous are modeled other than algae uptake.

Available carbon is more difficult to model because of the carbonate chemical equilibrium system and exchange of dissolved inorganic carbon with the atmosphere. Alkalinity and pH are involved in estimating available inorganic carbon (CO_2) for algae growth. Total CO_2 flowing into the reservoir is calculated from pH and alkalinity measurements. Alkalinity is modeled as a conservative quantity, without sinks or sources in the reservoir. As algae use CO_2, the pH increases and available CO_2 decreases. Respiration, decay, and sediment oxygen demand processes release CO_2 into the water column, and cause the pH to decrease. The calculated concentration of CO_2 is used to limit algae growth with a half-saturation coefficient. The carbon limit represents a combination of direct carbon availability and indirect pH limitations on algae growth. Potential algae growth rate increases with temperature to a maximum of 2.0 day^{-1} between 20° and 30°C, then decreases to 10 percent maximum as temperature increases. The potential growth rate may be limited by light or nutrients. Algae respiration increases to a maximum of 0.1 day^{-1} between 20° and 30° C. Algae mortality rate also increases to a maximum of 0.01 day^{-1} between 20° and 30° C. Algae settling rate was specified as 0.1 m/day. Algae mortality produces detritus, while respiration produces nutrients directly.

Branched Version Changes to BETTER for Lake Barkley

Incorporating branches did not alter the basic model concepts, but the connections between elements was complicated by the junctions and end elements of the branches. A new set of "flags" and "pointers" were developed to handle the possibilities of junctions, upper ends, lower ends connecting to the main channel, etc. This version can only handle simple branches; branches cannot themselves branch again. Each element is located along either the main channel of the reservoir or along a branch that connects directly to the main channel. Inflows can be located anywhere along the main channel, but only at the upstream ends of branches.

The subroutines needed to estimate daily flow patterns were modified to allow the required combination of upstream and downstream flows in branches and along the main channel. Inflows to the main channel move upstream and/or downstream. If a branch is encountered, flows move upstream to the end of the branch. Flows from the upstream end of a branch move downstream to the confluence with the main channel. Flows then split and move both upstream and downstream in the main channel. The longitudinal distribution of flows is based on the surface areas of the surface elements. Branches require flows to be split according to the surface areas of the branch and those beyond the branch on the main channel.

Once the flows and mixing exchanges are calculated, the mass balance computations are the same as in prior versions of the BETTER model, except that two new flow terms are possible, representing flows into or out of a branch. Only main channel columns at a branch confluence have these additional terms. The downstream end column of a branch transports downstream (positive) flow to the confluence column on the main channel, and receives any upstream (negative)

flow from the confluence column. These changes in the mass balance computations are summarized in Figure 4.

Branches must have at least two columns, and cannot branch into the first or last column of the main channel (equivalent to extending the main channel). Branch inflows can only be placed at the upstream end of a branch. Inflows can be located on any column of the main channel. For the Barkley application, two branches were segmented with inflows from Eddy Creek and Little River. Additional inflows were placed along the main channel to represent flows from Cheatham Dam, Red River, Yellow Creek, Cumberland Steam Plant thermal discharges, and the Barkley-Kentucky Canal.

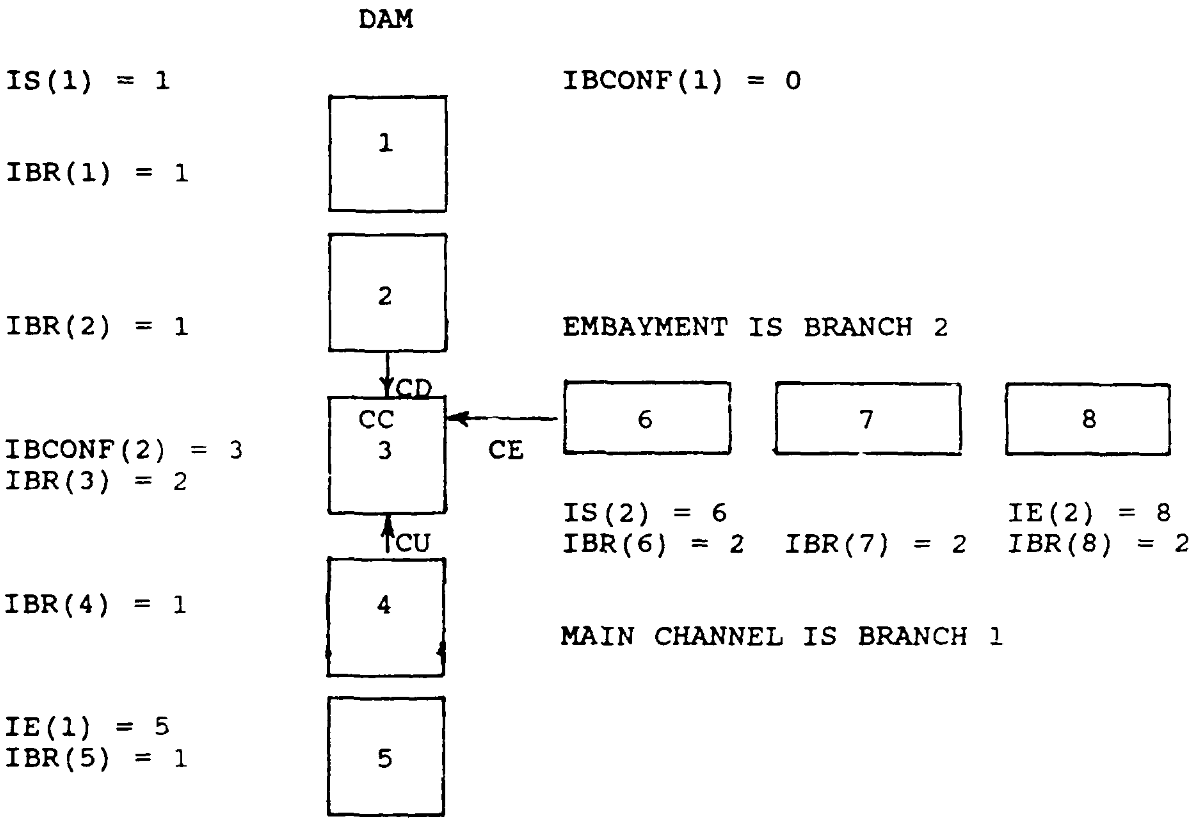
Modeling Procedures

The organization and manipulation of the model inflow files, coefficient value files, output files, and calibration data files is illustrated in Figure 5. Since three years were simulated, this set of files was repeated three times, except for the model code itself. The daily data for flows, meteorology, Cumberland Steam Plant operation, and Clarksville and Springfield intake measurements are read into the model inflow file generation program, GBKYR.FOR. When changes in the inflow concentrations were required, this program was run again to create a new inflow file, BKINYR.DAT.

The simulation run description for printout and appropriate coefficients were changed in the geometry and coefficient file, BARKGYR.DAT. A command file assigned the correct inflow file, coefficient file, and output files, and ran the program, BARKBETR.FOR, usually as a batch job on the TTU VAX 8800. The model run required 40 minutes of CPU time.

Figure 4

Mass Balance Terms for Branched BETTER Model



CC = Fraction of Volume Remaining
CB = Fraction of Volume From Below
CA = Fraction of Volume Frome Above

CU = Fraction of Volume From Upstream
CD = Fraction of Volume from Downstream
CI = Fraction of Volume from Inflow
CE = Fraction of Volume from Embayment

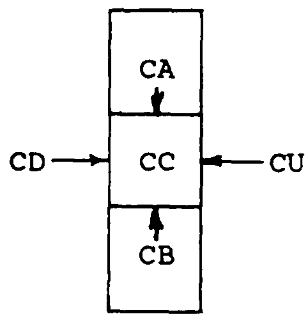
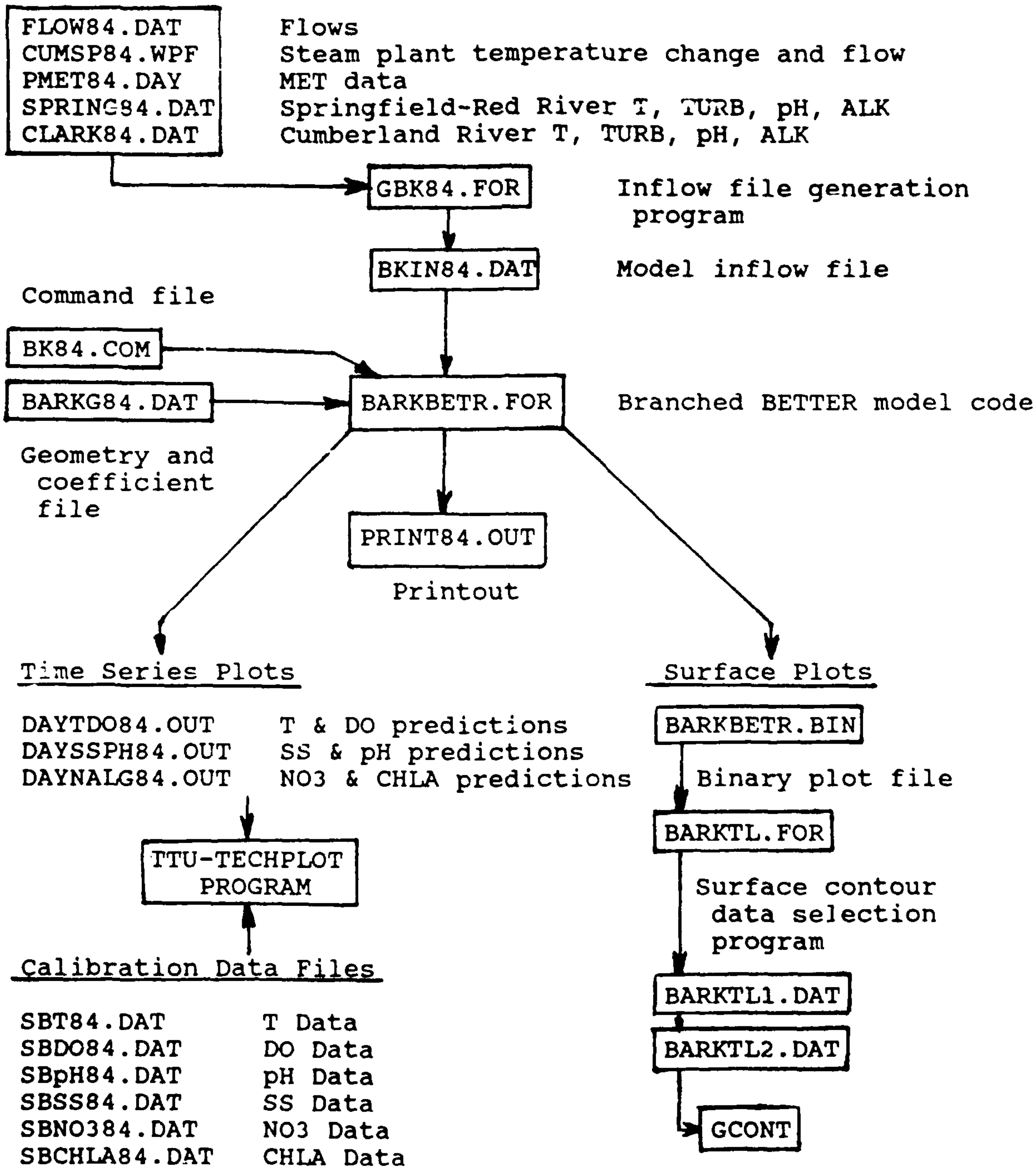


Figure 5


FLOW84.DAT
CUMSP84.WPF
PMET84.DAY
SPRING84.DAT
CLARK84.DAT
Flows
Steam plant temperature change and flow
MET data
Springfield-Red River T, TURB, pH, ALK
Cumberland River T, TURB, pH, ALK
GBK84.FOR
Inflow file generation program
BKIN84.DAT
Model inflow file
Command file
BK84.COM
BARKG84.DAT
BARKBETR.FOR
Branched BETTER model code
Geometry and coefficient file
PRINT84.OUT
Printout
Time Series Plots
DAYTDO84.OUT
DAYSSPH84.OUT
DAYNALG84.OUT
T & DO predictions
SS & pH predictions
NO3 & CHLA predictions
TTU-TECHPLOT PROGRAM
Calibration Data Files
SBT84.DAT
SBDO84.DAT
SBpH84.DAT
SBSS84.DAT
SBNO384.DAT
SBCHLA84.DAT
T Data
DO Data
pH Data
SS Data
NO3 Data
CHLA Data
Surface Plots
BARKBETR.BIN
Binary plot file
BARKTL.FOR
Surface contour data selection program
BARKTL1.DAT
BARKTL2.DAT
GCONT

The model creates a printout file, PRINTYR.OUT, which was printed if the simulation was successful to serve as a permanent record of the coefficients and results. Most of the analysis and comparison of the model results were accomplished with time series and contour graphics programs.

The time series plots were made using the TTU TechPlot program. These plots were generated from files of daily model predictions from segments corresponding to field data stations. Calibration data files for the six model variables were plotted along with the model predictions. The TechPlot program requires a command file for each plot. Two plots were combined onto a page with another "multiple plot" command file.

The surface contour plots were produced with another graphical package called GCONT. A program called BARKTL reads the appropriate surface values for the selected variable from the binary data file BARKBETR.BIN, for the main channel and the Little River embayment. Command files are edited for the variable name, year, and contour intervals, and the program GCONT produces the plots.

Geometry Data

Barkley Lake was segmented into 25 main channel columns and 8 embayment branch columns with a maximum of 10 layers as shown in Figure 6. This provided adequate resolution of longitudinal and vertical water quality gradients. The segment length of the first 15 columns in the downstream portion of the lake were three miles long, extending from Barkley Dam at CuRM 30.6 to CuRM 75. Five more segments were six miles long, extending to CuRM 105, just above the Cumberland Steam Plant located at CuRM 103. Five additional main channel segments were nine miles long, extending to Cheatham Dam at CuRM 148.7. The Little River embayment

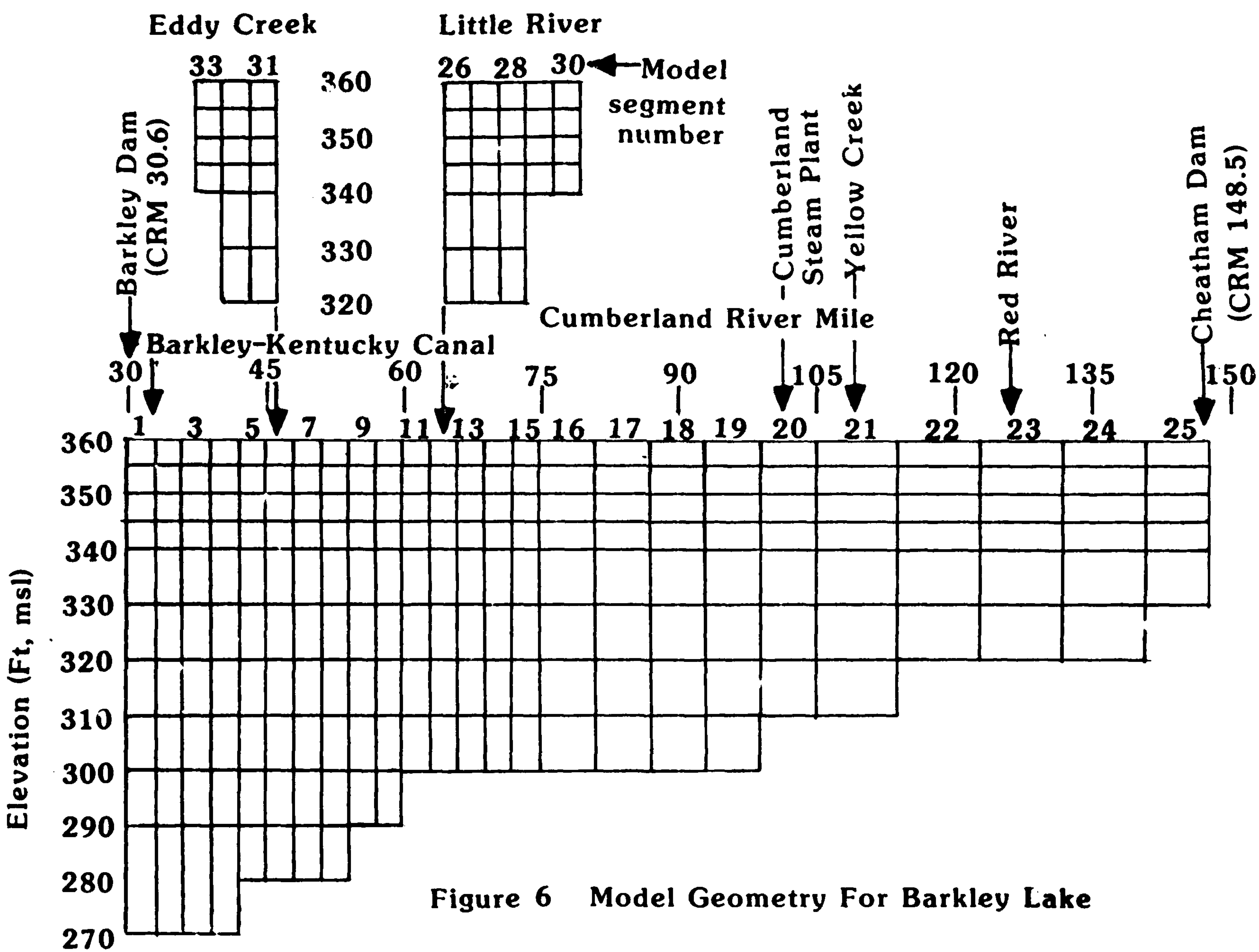


Figure 6 Model Geometry For Barkley Lake

was segmented as five three mile segments (Segments 26-30). Eddy Creek embayment was segmented as three columns, each three miles long (Segments 31-33).

Geometry data were obtained from sedimentation survey ranges (Nashville District Corps of Engineers, 1986) and some previously prepared GEDA channel cross sections, also provided by the Corps of Engineers. Both of these data sets emphasized the main channel, and so the embayment geometry had to be approximated from relatively few cross sections. The geometry data required by the model includes surface area, incremental volume, and incremental conveyance area for each column at several elevations. However, all of these values were calculated from channel widths and longitudinal segment lengths on a computerized spreadsheet. The specified widths could then be adjusted slightly to provide total areas and volumes that matched the elevation-area-volume curve for the entire lake. The resulting geometry data are shown in Tables 1-3. The cumulative areas and volumes correspond closely to those given for the entire project.

The geometry of the Barkley-Kentucky canal, the Cumberland Steam Plant intake and discharge channels, and the turbine intakes are important for accurately placing the corresponding flows into the model. The canal has a bottom elevation of 335 ft. msl. with a bottom width of approximately 400 feet. The outlet centerline for the canal was considered to be 350 ft. The Cumberland Steam Plant intake channel is located at CuRM 103.2. It contains a 1100 ft. long submerged skimmer wall that extends from the surface to elevation 314 ft. msl and withdraws water from near the bottom, which is at elevation 310 ft. The model outlet elevation for the cooling water was considered to be 320 ft. The discharge channel is slightly downstream at CuRM 102.9. This is a surface discharge with a flow distributor arrangement of nine 16 feet diameter corrugated

VOLUMES (1000 acft)

CuRM	31	33	36	39	42	45	48	51	54	57	60	63	66
SECT. NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
Elevation (ft)													
375	20.15	19.55	15.77	14.45	14.59	14.05	14.27	16.14	15.91	13.48	10.75	12.50	15.91
370	34.12	33.45	29.86	27.00	27.14	26.27	25.82	28.18	28.64	25.23	19.77	22.27	28.18
360	22.48	24.45	22.91	20.55	20.64	20.05	19.45	22.09	20.18	16.14	13.86	17.23	19.64
350	9.47	12.02	11.91	11.14	11.05	10.64	10.05	11.55	8.95	5.91	6.27	8.64	8.18
340	4.08	5.20	4.95	5.14	4.86	4.59	5.09	4.91	3.64	2.95	2.82	2.86	2.68
330	2.06	2.73	2.55	2.55	2.45	2.45	3.41	3.39	2.30	2.00	1.91	1.86	1.77
320	1.76	2.45	2.14	1.95	2.00	2.14	2.09	2.07	2.00	1.66	1.55	1.50	1.41
310	1.52	2.14	1.86	1.73	1.82	1.86	1.73	1.68	1.66	1.39	0.95	0.64	0.59
300	1.06	1.45	1.27	1.23	1.30	1.25	0.95	0.73	0.73	0.64	0.27	0.00	0.00
290	0.61	0.73	0.55	0.45	0.43	0.39	0.18	0.00	0.00	0.00	0.00	0.00	0.00
280	0.21	0.23	0.14	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
270	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	69	72	75	81	87	93	99	105	114	123	132	141
	14	15	16	17	18	19	20	21	22	23	24	25
	14.32	14.32	35.45	31.32	19.91	16.91	15.45	15.14	12.89	10.16	5.86	4.55
	25.00	23.18	55.45	46.64	28.45	23.55	20.36	21.95	18.00	14.05	9.82	8.00
	16.14	14.27	31.18	24.09	14.18	11.64	8.91	12.68	12.55	10.09	7.23	5.89
	5.82	5.27	9.55	8.91	7.91	6.73	5.73	7.77	7.64	6.68	4.91	2.98
	2.48	2.39	4.77	4.91	4.68	4.18	3.82	5.05	4.64	4.09	2.73	0.85
	1.80	1.70	3.32	3.36	3.23	2.82	2.45	2.59	1.50	1.23	0.55	0.00
	1.41	1.27	2.36	2.36	2.18	1.36	0.73	0.55	0.00	0.00	0.00	0.00
	0.59	0.50	0.91	0.91	0.82	0.36	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

EMBAYMENT VOLUMES (1000 ac.ft)

	Eddy Creek				Little River				Total Reservoir Volume				
	0	3	6	9	0	3	6	9	12	Layer			Model/
	31	32	33	39	26	27	28	29	30	Model	Model	Actual	Actual %
Elevation (ft)													
375	0.68	0.55	0.41	0.00	8.52	8.18	4.09	2.39	1.18	420	2041	2082	98
370	1.18	0.93	0.66	0.00	16.30	14.95	6.36	3.41	1.68	696	1621	1642	99
360	1.00	0.75	0.50	0.00	14.18	12.64	4.55	2.05	1.00	465	925	928	100
350	0.82	0.55	0.34	0.00	7.07	6.09	2.05	0.77	0.32	224	460	453	102
340	0.64	0.36	0.18	0.00	1.36	0.91	0.32	0.09	0.00	102	236	230	103
330	0.45	0.18	0.05	0.00	0.73	0.41	0.09	0.00	0.00	58	134	132	102
320	0.23	0.05	0.00	0.00	0.23	0.09	0.00	0.00	0.00	38	76	75	101
310	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24	39	39	99
300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11	15	15	98
290	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3	4	4	101
280	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	1	1	80
270	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	100

Table 1 Barkley Lake Model Volumes

IV. CONVEYANCES (1000 sq.ft)

CuRM	31	33	36	39	42	45	48	51	54	57	60	63	66
SECT. NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
Elevation (ft)													
375	105.00	61.25	46.25	40.50	39.00	41.25	36.00	42.50	46.25	41.25	32.88	26.25	42.50
370	185.00	96.50	87.50	76.75	71.75	77.50	67.00	75.00	80.00	77.50	61.25	47.50	75.00
360	115.00	70.50	64.00	62.00	51.00	62.50	47.75	59.25	62.25	48.75	40.00	36.25	58.50
350	42.75	35.38	30.75	34.75	26.50	34.25	24.25	31.00	32.50	16.75	15.75	18.75	28.75
340	17.75	15.88	12.75	14.50	13.75	13.00	12.25	15.75	11.25	8.75	7.50	8.00	7.75
330	8.75	8.25	6.75	7.25	6.75	6.75	6.75	12.00	6.63	6.00	5.00	5.50	4.75
320	7.25	7.25	6.25	5.50	5.25	5.75	6.00	5.50	5.88	5.13	4.00	4.50	3.75
310	6.25	6.25	5.50	4.75	4.75	5.25	5.00	4.50	4.75	4.38	3.25	2.00	1.50
300	4.50	4.25	3.75	3.25	3.50	3.63	3.25	2.00	2.00	2.00	1 50	0.00	0.00
290	2.75	2.25	1.75	1.25	1.25	1.13	1.00	0.00	0.00	0.00	0.00	0.00	0.00
280	1.00	0.75	0.50	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
270	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

69	72	75	81	87	93	99	105	114	123	132	141	149
14	15	16	17	18	19	20	21	22	23	24	25	34
45.00	33.75	45.00	52.50	33.63	21.13	25.38	17.13	10.63	13.00	5.63	5.13	4.25
80.00	57.50	70.00	82.50	45.75	32.50	32.25	23.75	16.50	16.50	9.25	8.75	7.75
49.50	39.25	39.25	46.50	19.75	19.25	12.75	11.75	11.50	11.50	7.00	6.25	5.90
16.25	15.75	13.25	13.00	11.50	10.25	8.25	7.50	6.75	7.25	5.00	4.00	2.15
7.00	6.63	6.50	6.63	6.88	6.00	5.50	5.00	4.25	4.25	3.25	1.75	0.00
5.00	4.88	4.50	4.63	4.63	4.25	3.50	3.25	1.50	1.25	1.00	0.00	0.00
4.00	3.75	3.25	3.25	3.25	2.75	1.00	1.00	0.00	0.00	0.00	0.00	0.00
1.75	1.50	1.25	1.25	1.25	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

IV. CONVEYANCES (1000 sq.ft)]

	Eddy Creek				Little River						Yellow &		
	0	3	6	9	0	3	6	9	12	15	Red River	Steam	Canal
	31	32	33	39	26	27	28	29	30	38	35 & 36	37	40
Elevation (ft)													
375	2.125	1.625	1.375	0.875	15.625	31.25	13.75	8.75	4.375	2.125	1	1.25	7.5
370	3.75	2.75	2.375	1.25	29.875	59.75	22.5	12.5	6.25	3	1.75	2.4	9
360	3.25	2.25	1.875	0.875	26	52	17.5	7.5	3.75	1.75	1.5	2.3	8
350	2.75	1.75	1.25	0.625	13.625	25.25	8.25	3	1.25	0.5	1.25	2.2	7
340	2.25	1.25	0.75	0.25	3.75	3.75	1.25	0.5	0	0	1	2.1	6
330	1.75	0.75	0.25	0	2.25	1.75	0.5	0	0	0	0.75	0	0
320	1	0.25	0	0	0.75	0.5	0	0	0	0	0	0	0
310	0.25	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2 Barkley Lake Model Conveyance Areas

SURFACE AREAS (acres)

CuRM	31	33	36	39	42	45	48	51	54	57	60	63	66
SECT. NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
Elevation (ft)													
375	4424	4364	3245	2991	3018	2900	2991	3455	3364	2764	2218	2636	3364
370	3636	3455	3064	2791	2818	2718	2718	3000	3000	2627	2082	2364	3000
360	3188	3236	2909	2609	2609	2536	2445	2636	2727	2418	1873	2091	2636
350	1309	1655	1673	1500	1518	1473	1445	1782	1309	809	900	1355	1291
340	585	750	709	727	691	655	564	527	482	373	355	373	345
330	230	291	282	300	282	264	455	455	245	218	209	200	191
320	182	255	227	209	209	227	227	223	214	182	173	173	164
310	170	236	200	182	191	200	191	191	186	150	136	127	118
300	133	191	173	164	173	173	155	145	145	127	55	0	0
290	79	100	82	82	86	77	36	0	0	0	0	0	0
280	42	45	27	9	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0

	69	72	75	81	87	93	99	105	114	123	132	141
	14	15	16	17	18	19	20	21	22	23	24	25
	3091	3182	8000	6836	4091	3509	3164	3245	3164	2509	1282	970
	2636	2545	6182	5691	3873	3255	3018	2809	1991	1555	1064	848
	2364	2091	4909	3636	1818	1455	1055	1582	1609	1255	900	752
	864	764	1327	1182	1018	873	727	955	900	764	545	427
	300	291	582	600	564	473	418	600	627	573	436	170
	195	186	373	382	373	364	345	409	300	245	109	0
	164	155	291	291	273	200	145	109	0	0	0	0
	118	100	182	182	164	73	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0

Embayment Surface Areas (acres)

	Eddy Creek				Little River					Reservoir Areas		Model/
	0	3	6	9	0	0	6	9	12			
	31	32	33	39	26	27	28	29	30	Model	Actual	Actual %
Elevation (ft)												
375	145	118	91		1745	1709	909	545	273	90312	93430	97
370	127	100	73		1664	1564	727	409	200	77603	82580	94
360	109	86	59		1595	1427	545	273	136	61571	60270	102
350	91	64	41		1241	1100	364	136	64	31463	32820	96
340	73	45	27		173	118	45	18	0	13268	13310	100
330	55	27	9		100	64	18	0	0	7176	7050	102
320	36	9	0		45	18	0	0	0	4400	4360	101
310	9	0	0		0	0	0	0	0	3106	2700	115
300	0	0	0		0	0	0	0	0	1633	1160	141
290	0	0	0		0	0	0	0	0	542	470	115
280	0	0	0		0	0	0	0	0	124	60	207
270	0	0	0		0	0	0	0	0	0	0	100

Table 3 Barkley Lake Model Surface Areas

pipes with bottom elevations of 330 ft. These submerged pipes force warm water along the bottom of the channel and keep cool reservoir water from intruding along the bottom of the channel and mixing with the heated discharge. The warm effluent rises and spreads out at the surface, and was considered to be a surface inflow in the model. The intakes to the turbines in the Barkley powerhouse enter trashracks that extend 45 feet from the bottom. The centerline of the penstocks is 310 ft., which was the modeled outlet elevation for releases from Barkley Dam. Spillway flows were not separately considered in this modeling study, although the spillway crest elevation is slightly higher at 325 ft.

Daily Flows

The Barkley model requires daily inflow volumes for each of the inflows and outflows. These are:

Inflows

1) Cumberland River (releases from Cheatham)

2) Red River (USGS streamflow gage at Port Royal, TN)

3) Yellow Creek (USGS streamflow gage at Ellis Mills, TN)

4) Cumberland Steam Plant (thermal discharge)

5) Little River (USGS streamflow gage at Cadiz, KY)

6) Eddy Creek (fraction of Little River flows)

7) Barkley-Kentucky Canal (USGS flow gage in canal)

8) Local Inflows (multiple of Little+Yellow+Red flows)

Outflows

1) Barkley Dam (turbine and spillway combined)

2) Barkley-Kentucky Canal (USGS flow gage in canal)

3) Cumberland Steam Plant Intake (for cooling water)

The specified inflows and outflows must balance the recorded change in lake volume as calculated from the midnight elevations at Barkley Dam. Each of these measured and estimated flows have some uncertainty. Some rule must be used to adjust these inflows and outflows to correspond to the daily volume fluctuations, although the midnight elevations may not be an accurate indication of reservoir storage during high flow events, when considerable wedge storage may exist in the upstream reaches of the reservoir (Granju, 1981). It was decided that the measured canal flows should be adjusted to close the water budget for the lake. The recorded canal flows were usually quite close to the back-calculated canal flows except during some high flow events. These water budget calculations confirmed the validity of the flow and release measurements available for Lake Barkley. Results of daily water budget computations made by the reservoir operations section of the Corps could be used in future applications.

The seasonal pattern of flows through Barkley Lake strongly influences water quality response by controlling the residence time. The local inflows from the tributary streams can be an equally important factor in water quality patterns because these inflows can be a major source of organic materials, suspended sediment particles, and nutrients. These local inflow effects are especially important in the embayments which receive the initial flush of materials from these local watersheds.

The measured hydrographs from Little River, Yellow Creek, and Red River are shown in Figures 7 for 1984, 1985, and 1986. During 1984, several winter and spring storms produced sustained runoff. A major storm runoff event occurred in May of 1984, with little additional runoff until November. A series of small storms occurred during 1985, with a June event recorded on the Red River, and a July event on the Little River. The remainder of the summer and fall was

Figure 7 Tributary Flows for 1984-1986

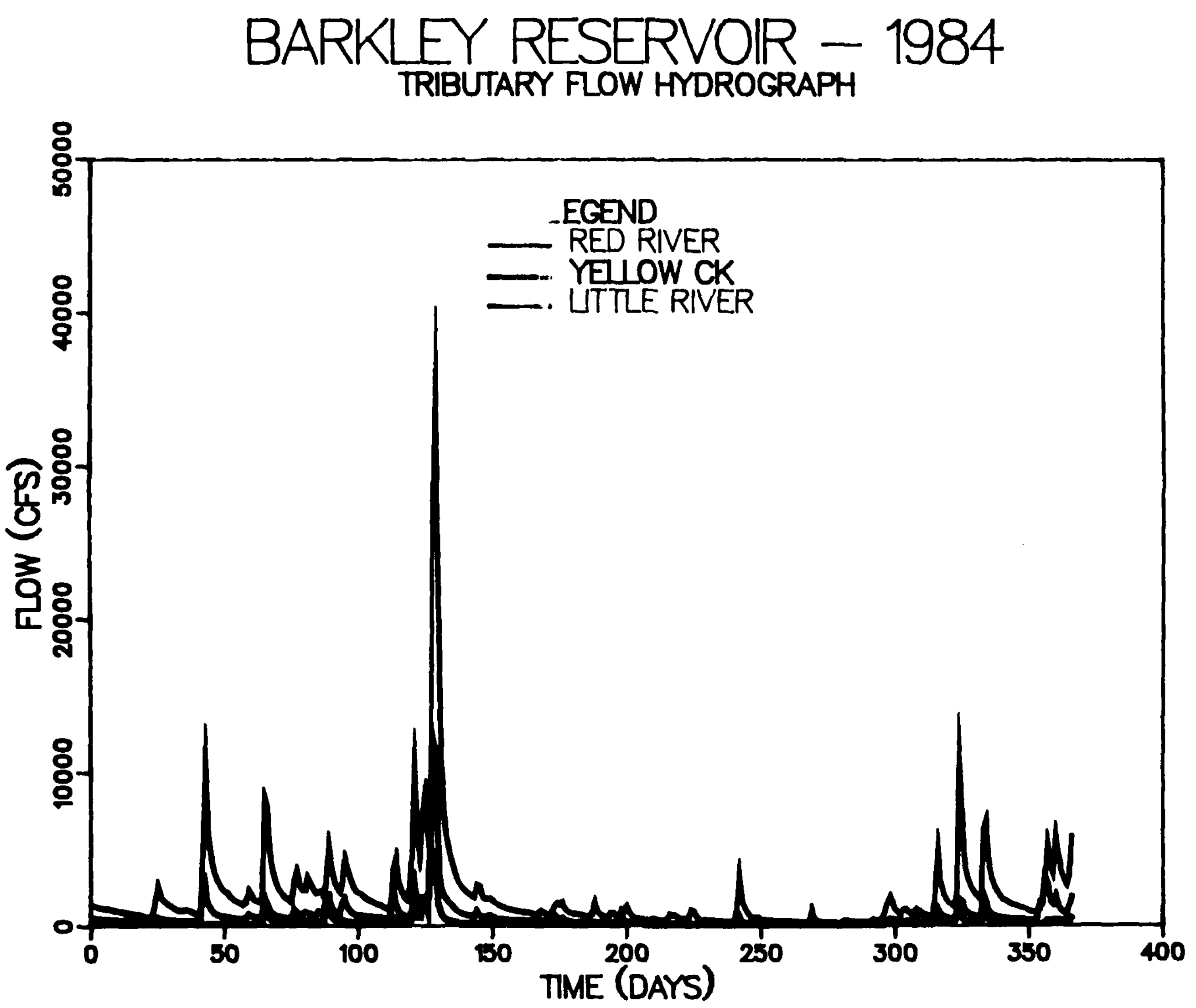
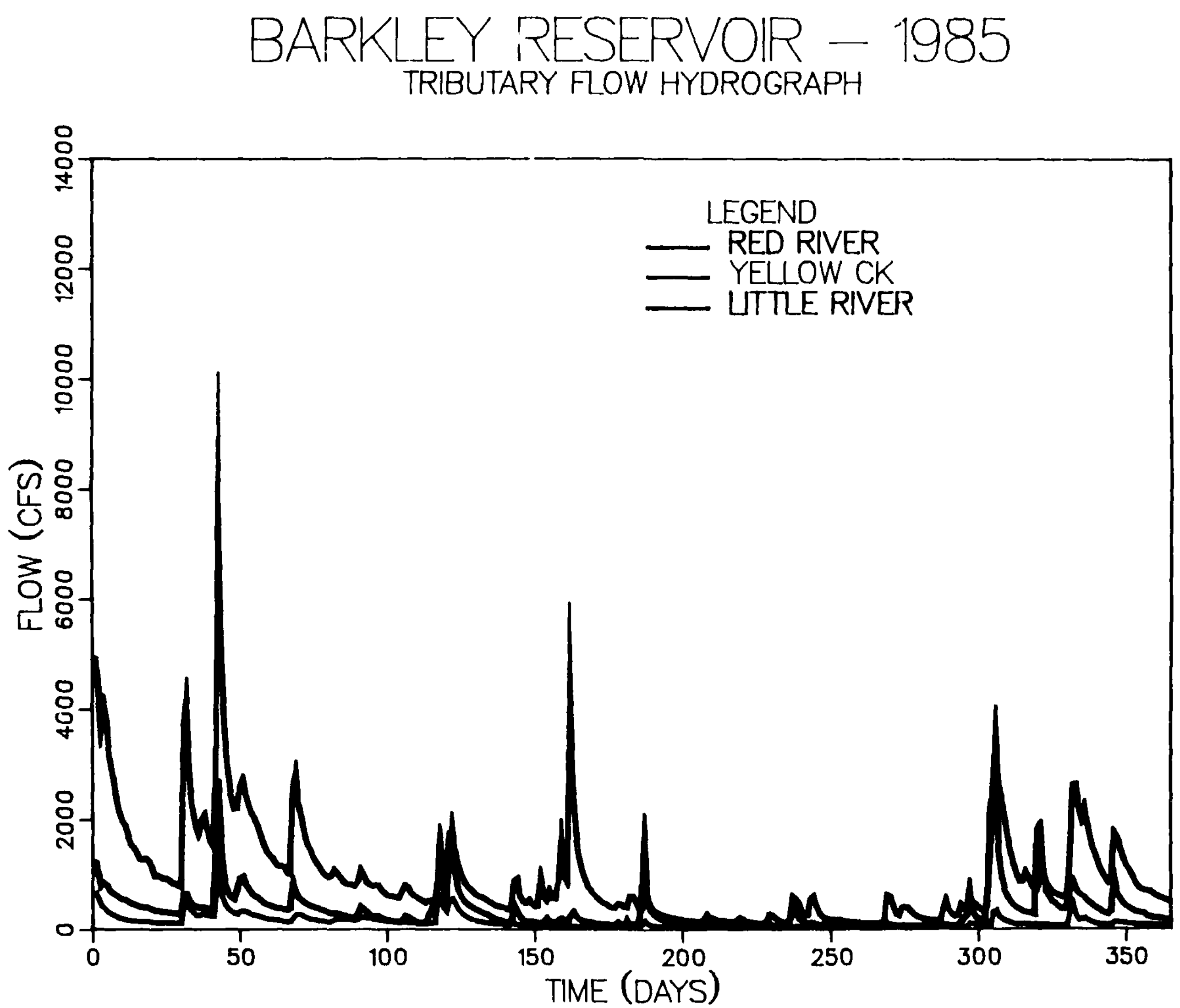


Figure 7 (continued)



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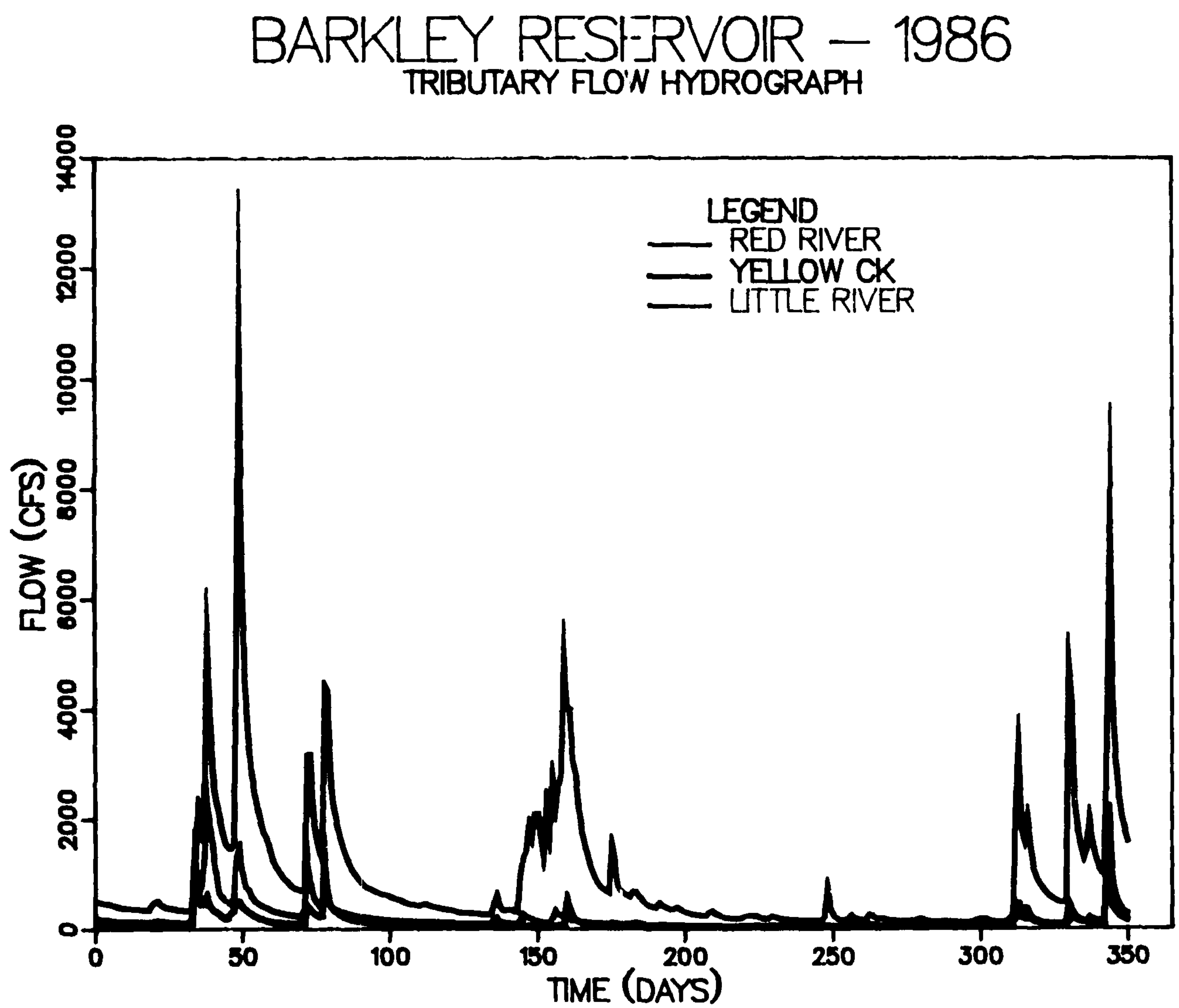


quite dry. January of 1986 was exceptionally dry. Some winter storms produced runoff in February and March. April and May were dry. A significant flow event was recorded on the Red River in June, but not on the other streams. Summer and fall flows were again quite low.

Inflowing Water Quality Data

The Barkley model requires daily temperatures and concentrations for each of the variables at each inflow location. Most of this data is not measured and must be estimated from a few periodic samples. This is accomplished with the inflow file generation program, which reads available data and interpolates or uses specified daily values for all required variables at each inflow. It is fortunate that some important data were available for this task. More inflow measurements should be obtained in the future to reduce the uncertainty in the modeled results.

The Clarksville water treatment plant intake is located on the Cumberland River approximately 15 miles downstream of Cheatham dam at CuRM 133. Raw water temperature, turbidity, pH, alkalinity, and hardness are recorded daily. Temperature and turbidity records are shown in Figure 8 for the three study years. These daily records are extremely important since they represent the inflow conditions from Cheatham Lake. No other release measurements are available for Cheatham. The inflow temperatures recorded at Clarksville and the intake temperatures recorded downstream at the Cumberland Steam Plant were nearly identical. These two independent measurements provide confirmation for the temperatures entering Lake Barkley.

Two water treatment plants are located on the Red River; Adams at river mile 34.1 and Springfield at mile 47.3. Although these are several days travel

Figure 8

Clarksville Water Intake Temperatures and Turbidities for 1984-1986

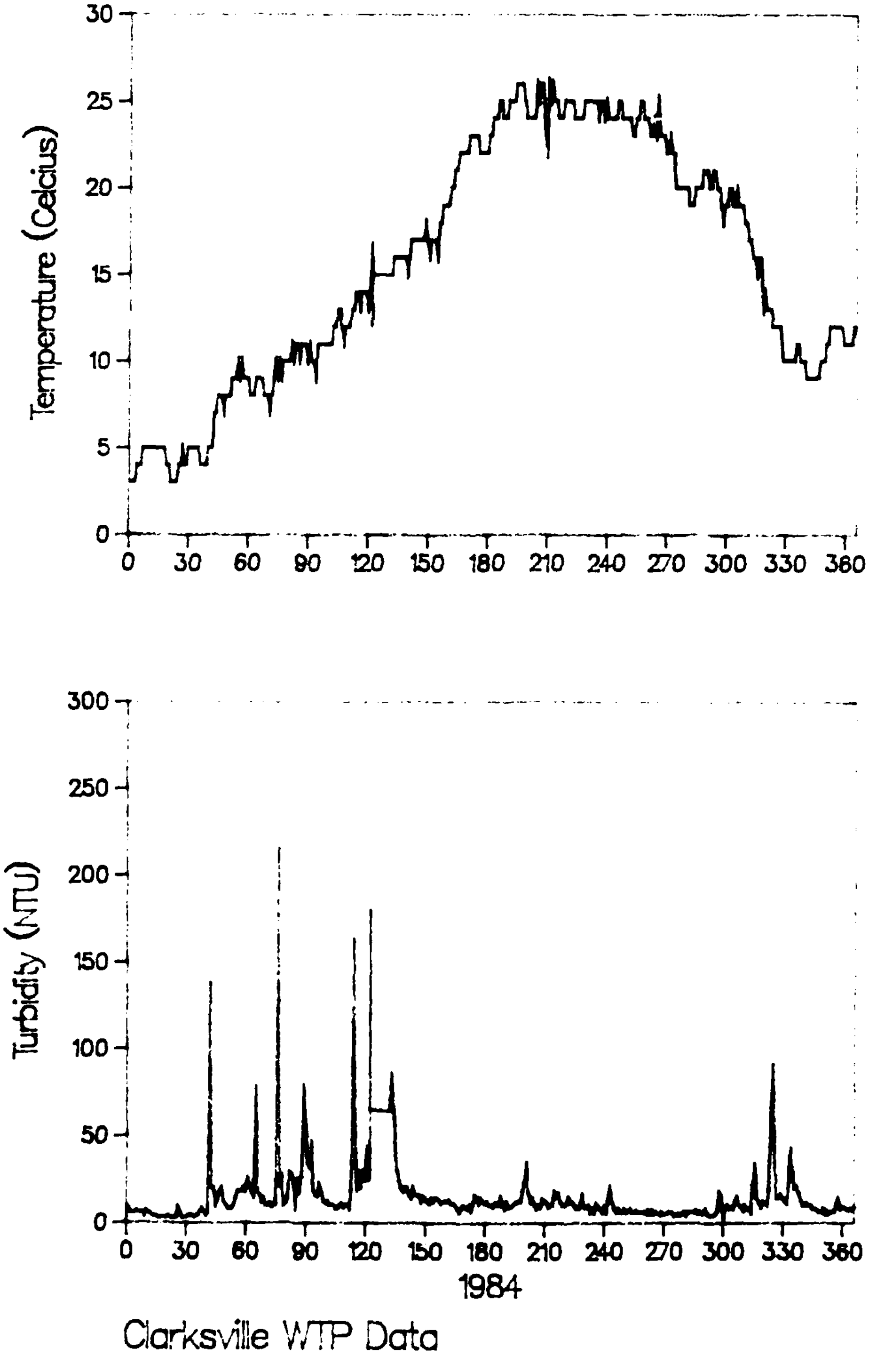
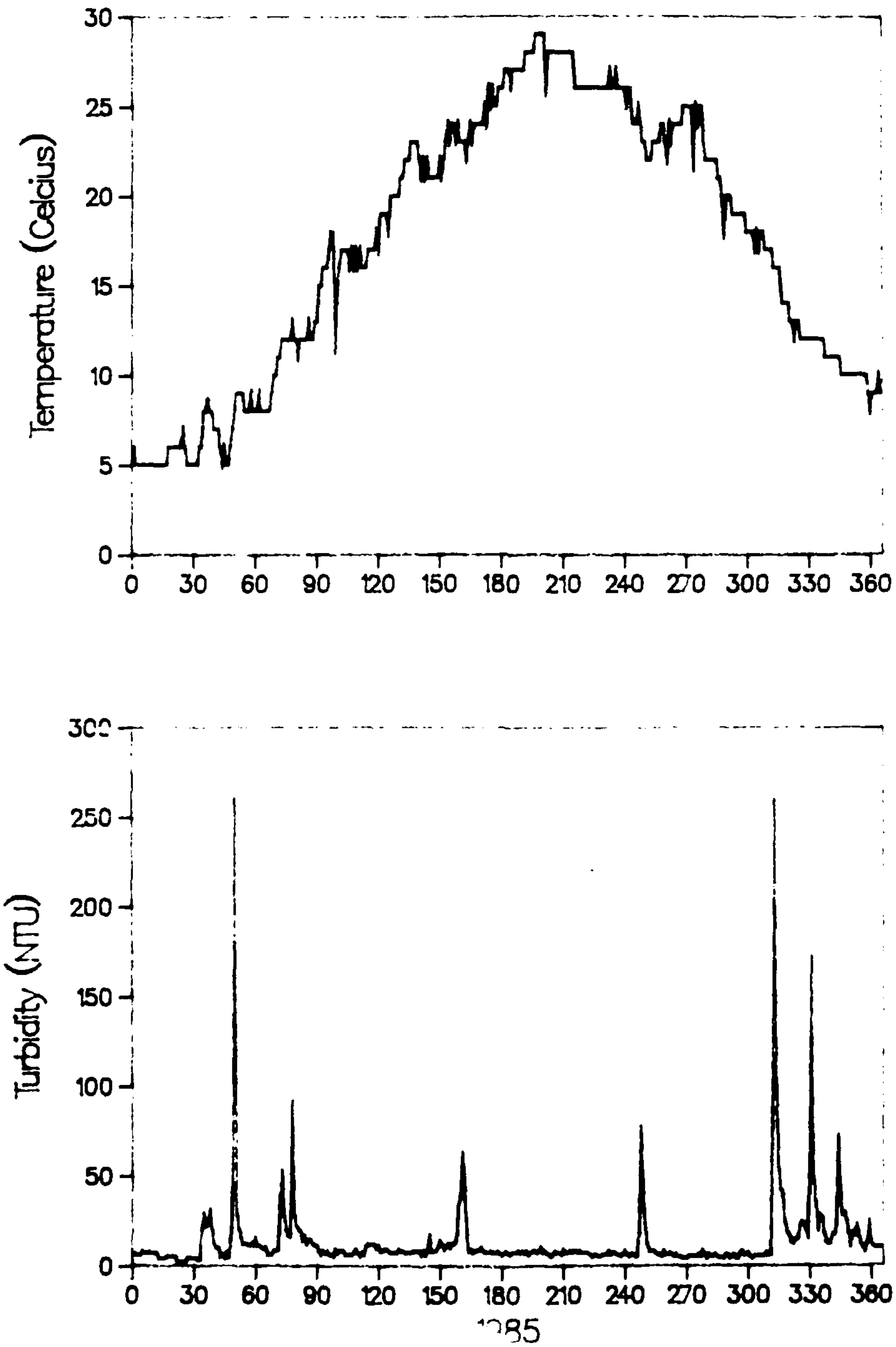
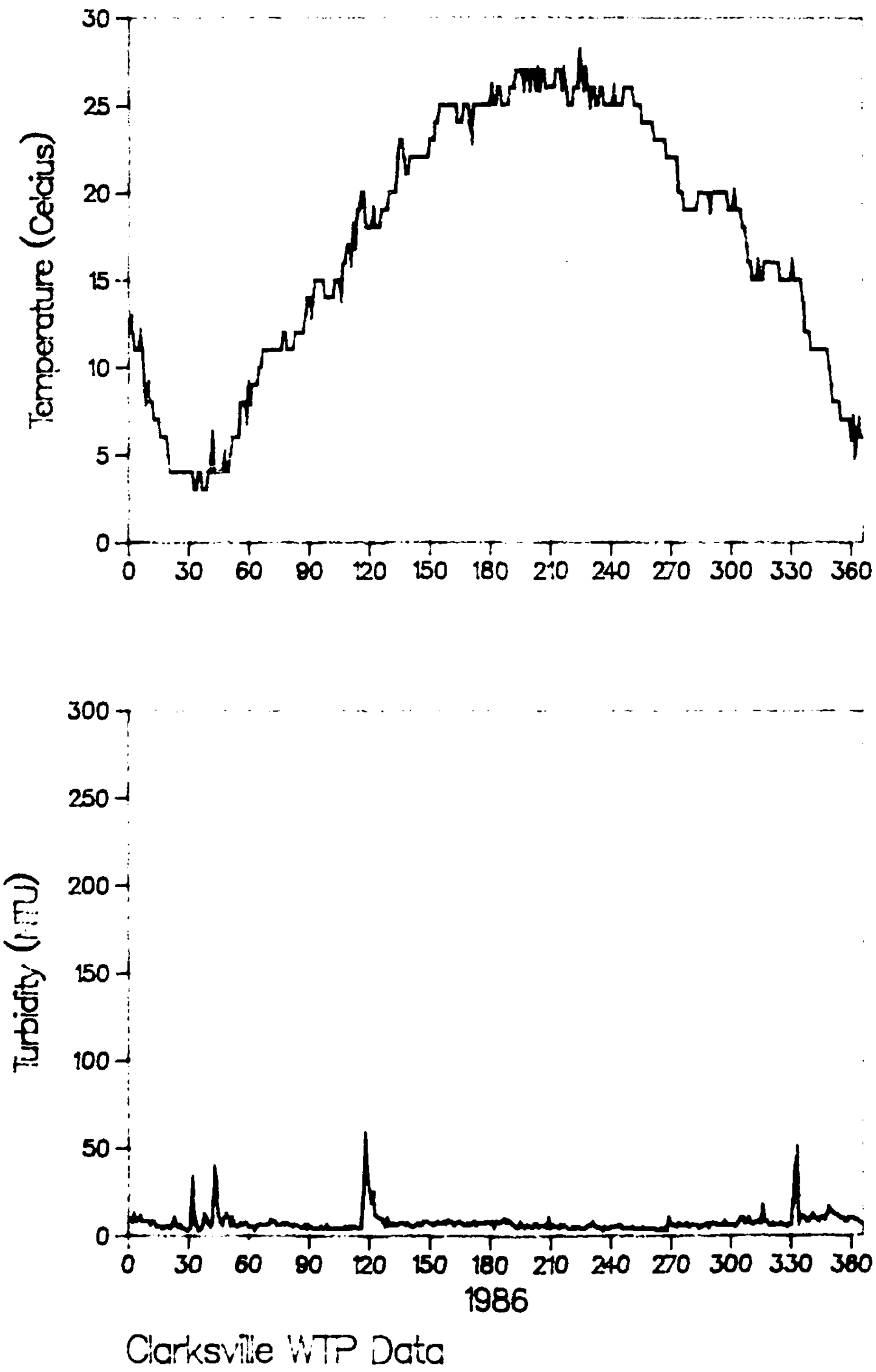


Figure 8 (continued)



Clarksville WTP Data

Figure 8 (continued)



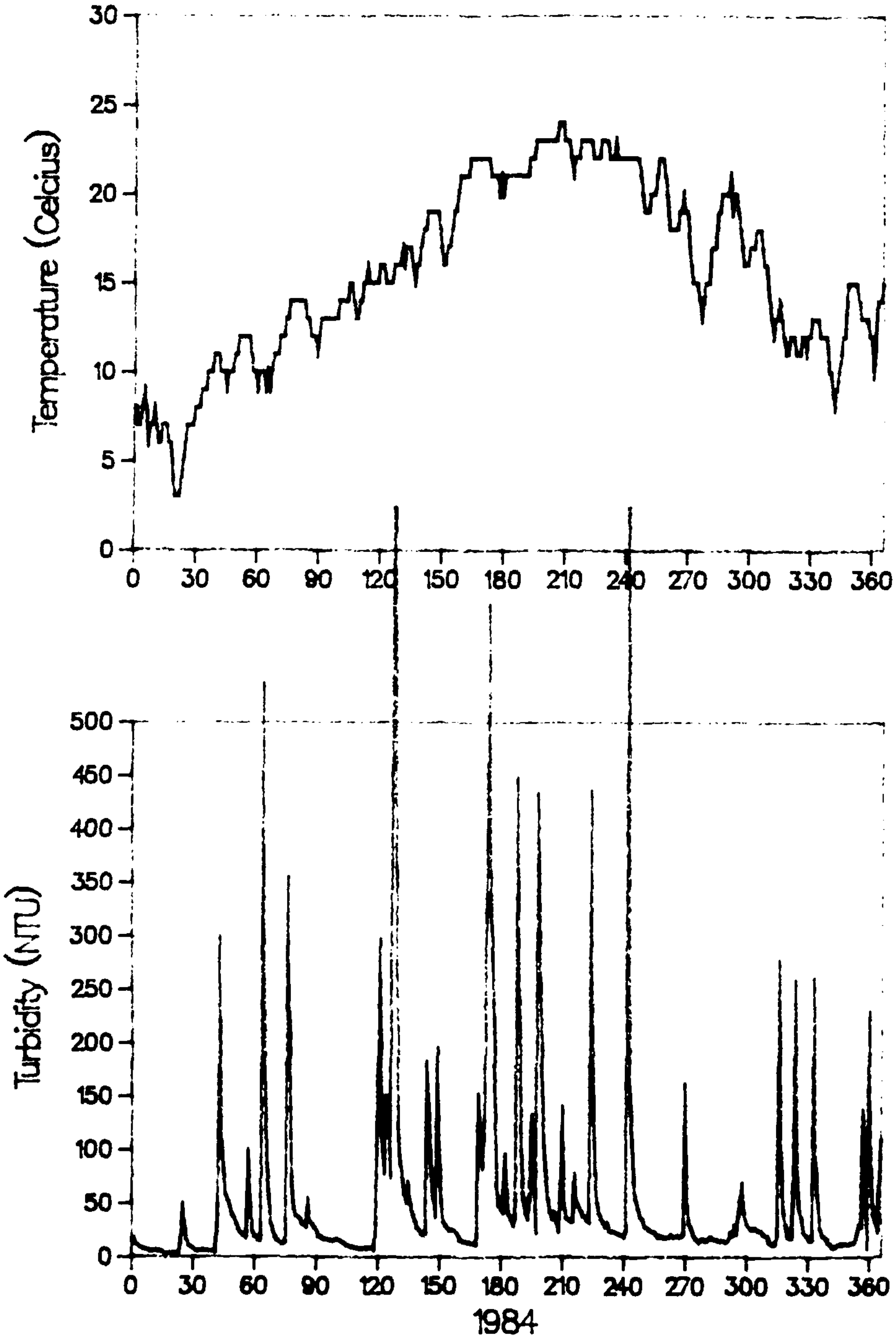
time upstream, they provide the only available local tributary records for temperature and turbidity. Adams had missing records during 1984 and 1985, so Springfield data were used. The temperature and turbidity data from Springfield are shown in Figure 9 for 1984-1986. Comparison of the records from these two locations showed significant differences at times.

These differences emphasize the importance of accurate inflow temperature and concentration measurements at the major tributaries. For this modeling, all other tributary inflows were assumed to have the same temperature and turbidity as Springfield, which may have been an overestimate of turbidity and an underestimate of temperature. It was helpful to have these two sets of daily data for the Cumberland and Red River inflows. Additional efforts to obtain accurate tributary inflow temperatures and concentrations are recommended. Inflow measurements of model variables at a range of flow conditions would be useful for future modeling and management purposes. Water quality monitors and automatic pump samplers at stream gages might be utilized.

Other water quality variables had to be estimated from periodic measurements from these streams. Unfortunately, there have been relatively few water quality surveys in this downstream portion of the Cumberland River basin. The USGS operated a bi-monthly NASQUAN sampling station in Barkley tailwater from 1968 through 1986, but this station has been discontinued. A summary of this data is provided in Table 4. Nutrients, organic material (BOD), chlorophyll, and suspended sediment data are perhaps the most important variables. However, BOD and chlorophyll were not measured, and many of the other variables fluctuate seasonally and during major storm events. Constant value assumptions were made for these model investigations. Chlorophyll values were set at 5.0 A μg/L for all inflows. This corresponds to algae biomass of 1 mg/L. Five day BOD values

Figure 9

Springfield Water Intake Temperatures and Turbidities for 1984-1986



Springfield WTP Data

Figure 9 (continued)

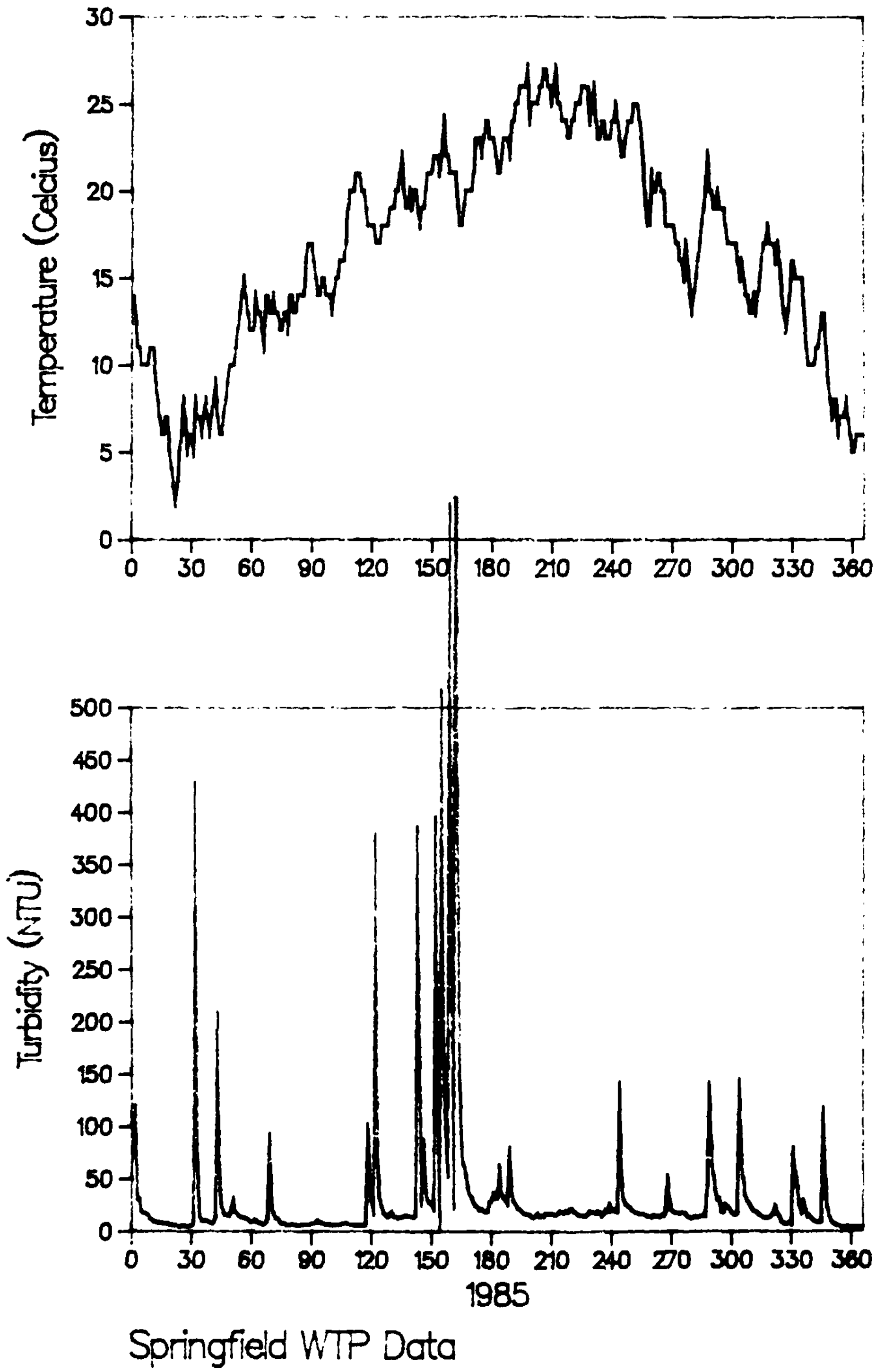


Figure 9 (continued)

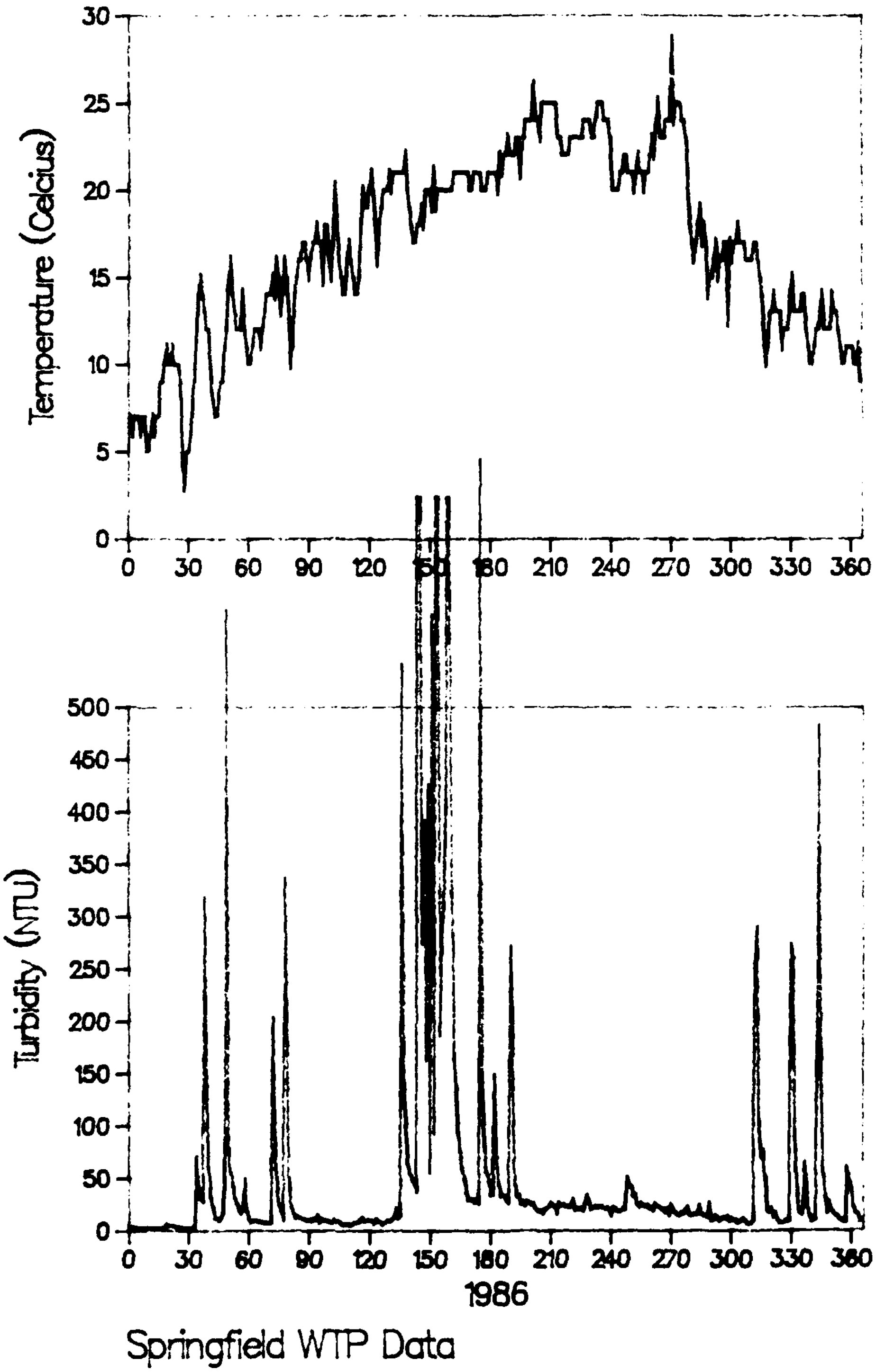


Table 4

Summary of Cumberland River Water Quality Data from the USGS NASQUAN Station, Downstream of Barkley Dam (1974-1986)

Variable	Quartile Values				
	0%	25%	50%	75%	100%
Temperature (°C)	2	10	17	26	30
Turbidity (NTU)	1	4	8	15	82
Suspended Sediment (mg/L)	3	12	18	27	167
Conductivity (μmhos/cm)	145	180	200	215	370
Total Dissolved Solids (mg/L)	86	105	116	129	162
pH	6.3	7.3	7.6	7.9	9.0
Alkalinity (mg/L)	47	64	71	84	120
Hardness (mg/L)	63	79	88	96	120
Organic + NH_3 - N (mg/L)	.05	.36	.45	.60	1.90
NO_3 - N (mg/L)	.01	.13	.31	.57	1.20
Total Phosphorous (mg/L)	.01	.07	.09	.11	.90
Total Organic Carbon (mg/L)	1.4	2.6	3.5	5.6	10.0
Sulfate (mg/L)	6	16	18	20	27
Total Iron (mg/L)	.18	.46	.60	.82	3.60

were assumed to be 2.5 mg/L for all inflows. The model assumed that this represents half the long-term BOD and that it was split equally between particulate detritus and dissolved organics. Ammonia-N was a constant 0.1 mg/L and nitrate-N was a constant 0.5 mg/L from all sources. Phosphorus was set at 0.1 mg/L for all inflows. This is assumed to be available for algal uptake and growth. Conductivity was set at 200 umhoes/cm from all tributaries. Dissolved oxygen was assumed to be saturated for the Cheatham release and all tributaries.

The inflow patterns for six important variables which were utilized for model simulations are shown in Figures 10 to 12 for the three years of simulation. For comparison, available field data at CuRM 133, which is upstream of Clarksville and the Red River inflow, and CuRM 100, which is downstream of the Cumberland Steam Plant and the inflow from Red River and Yellow Creek, are shown on these plots. Although both of these stations are in the upstream riverine portion of Barkley Lake, there are indications of longitudinal changes in these variables. Temperatures increased, as a result of both natural warming and thermal discharge effects. DO concentrations normally declined slightly, but sometimes increased between the two stations. The SS measurements were similar, but the pH data showed a consistent increase, apparently indicating significant algal activity in this upstream portion of the lake. This was confirmed by decreased nitrate and significant chlorophyll values in 1984. The upstream measurements of these variables were limited in 1985 and 1986. These upstream measurements suggest that significant water quality changes occur upstream of the Cumberland Steam plant, and that future surveys should not neglect this portion of the lake.

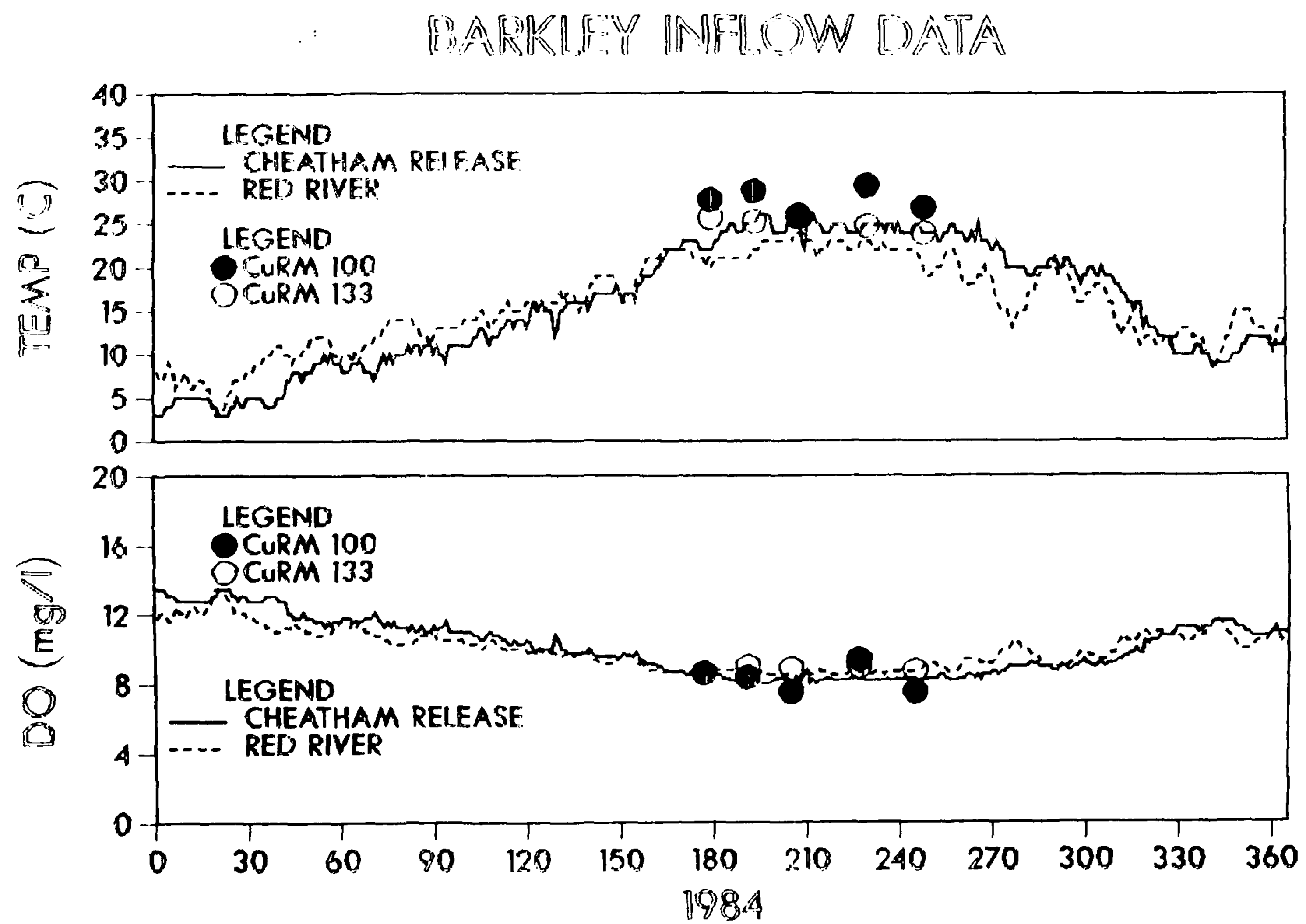


Figure 10 Modeled Inflow Conditions for 1984

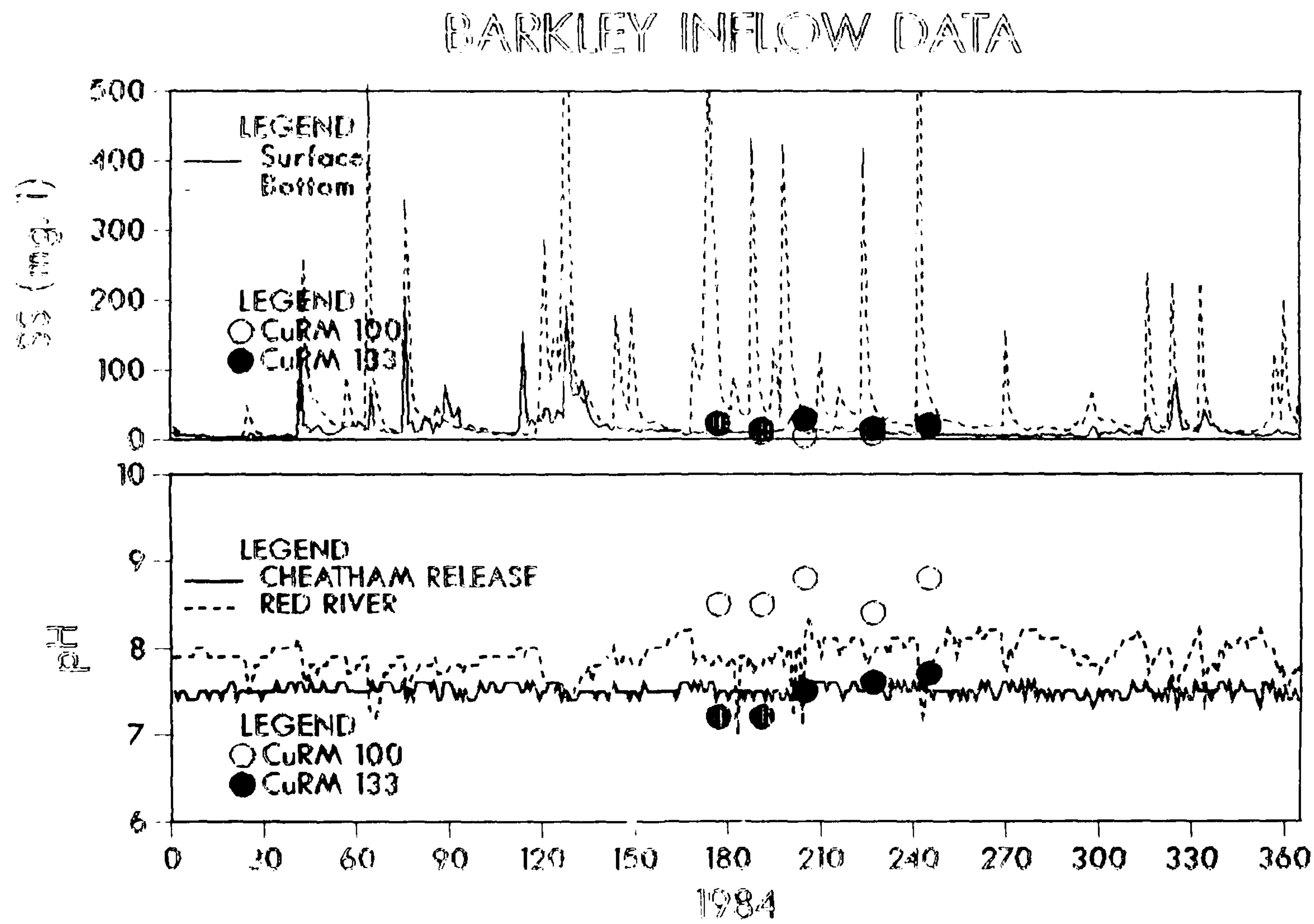


Figure 10 (continued)

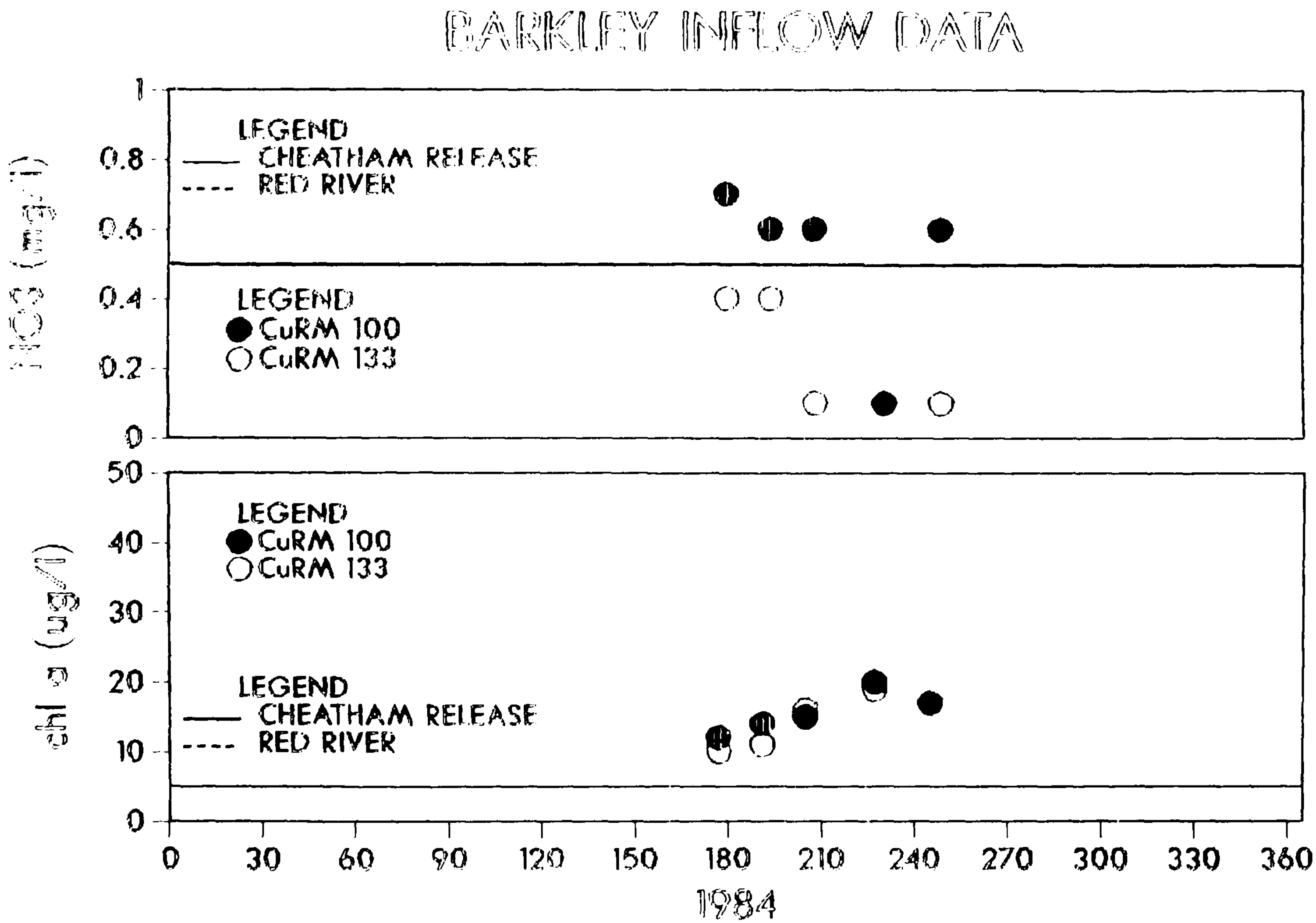


Figure 10 (continued)

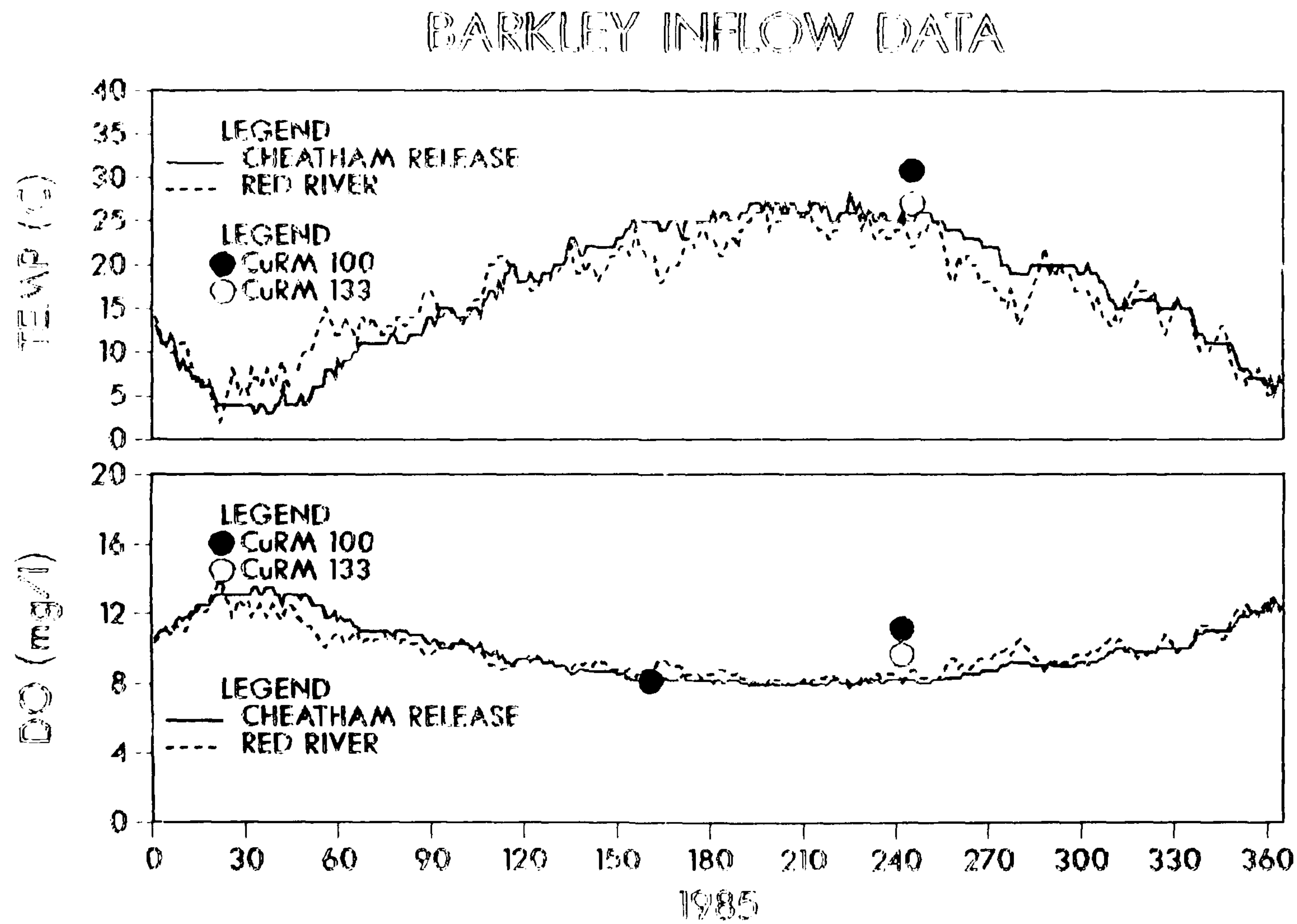


Figure 11 Modeled Inflow Conditions for 1985

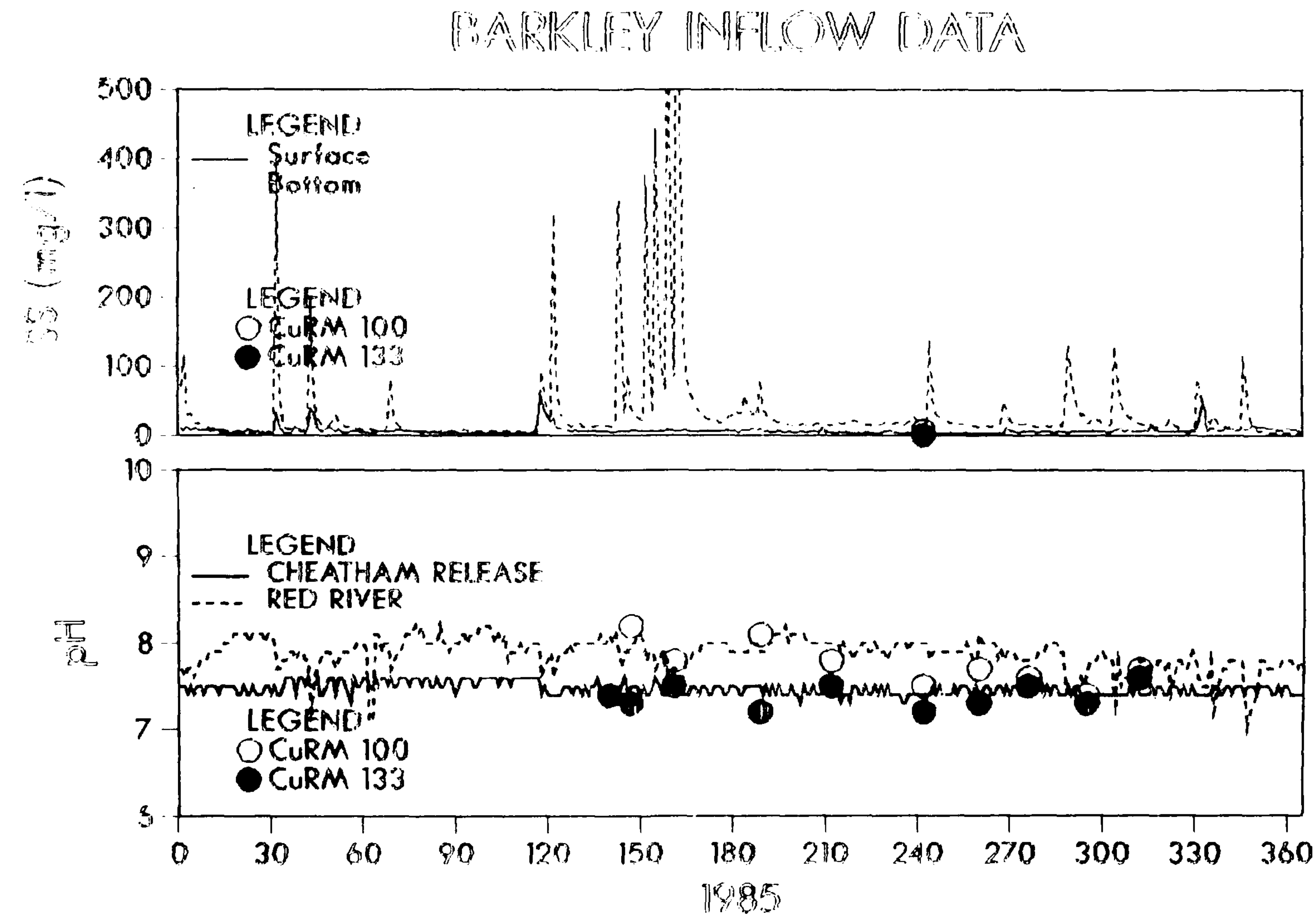


Figure 11 (continued)

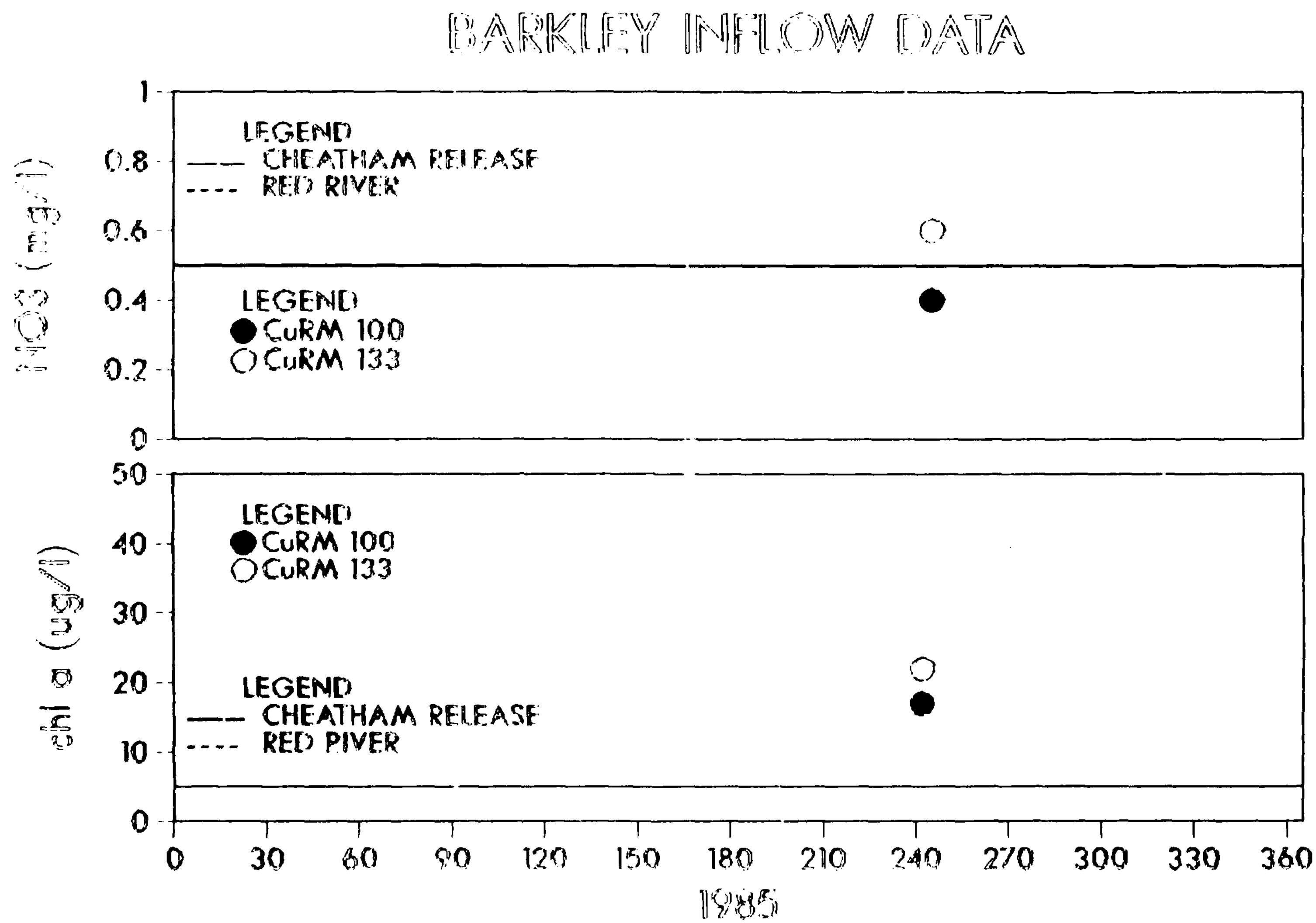


Figure 11 (continued)

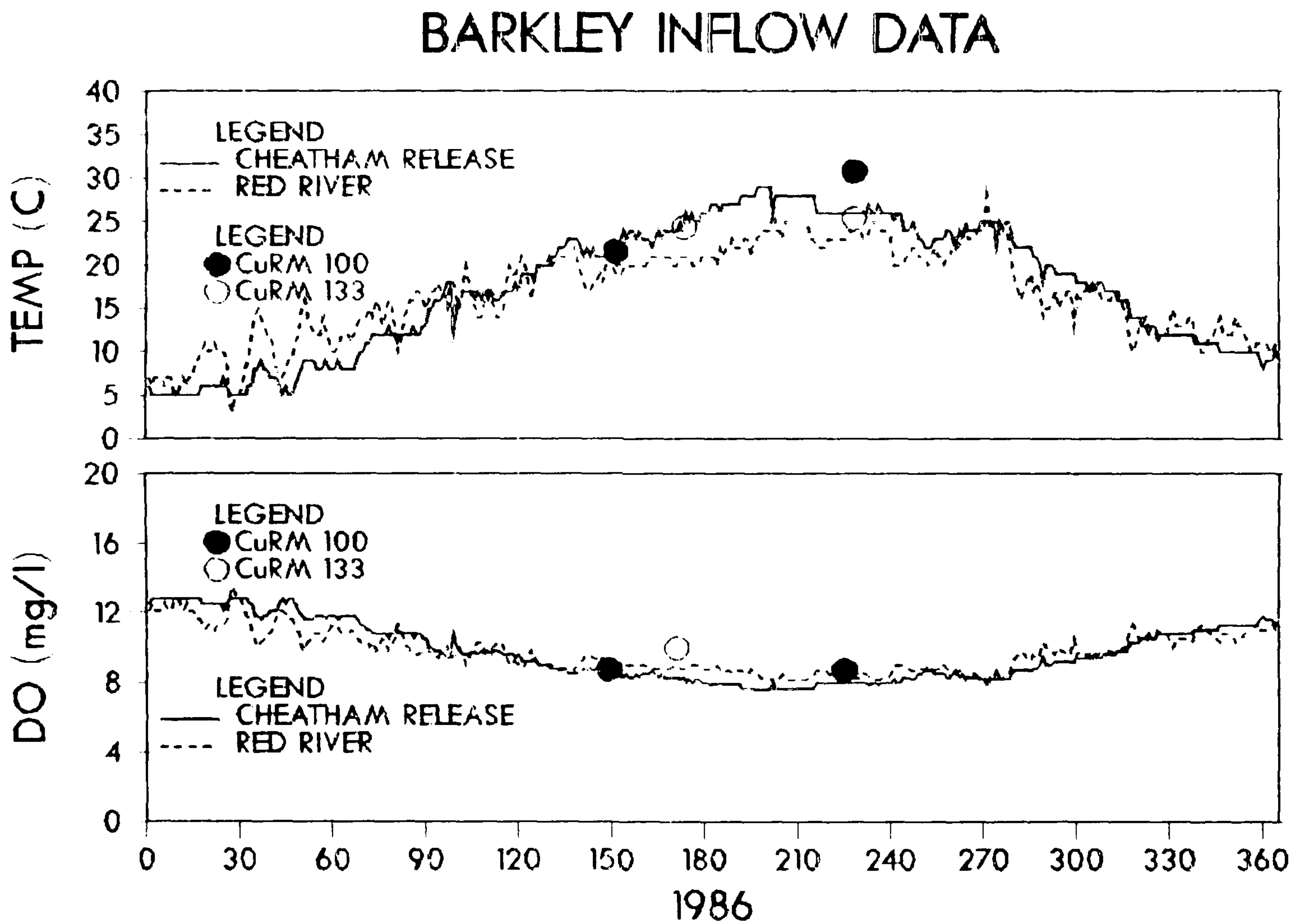


Figure 12 Modeled Inflow Conditions for 1986

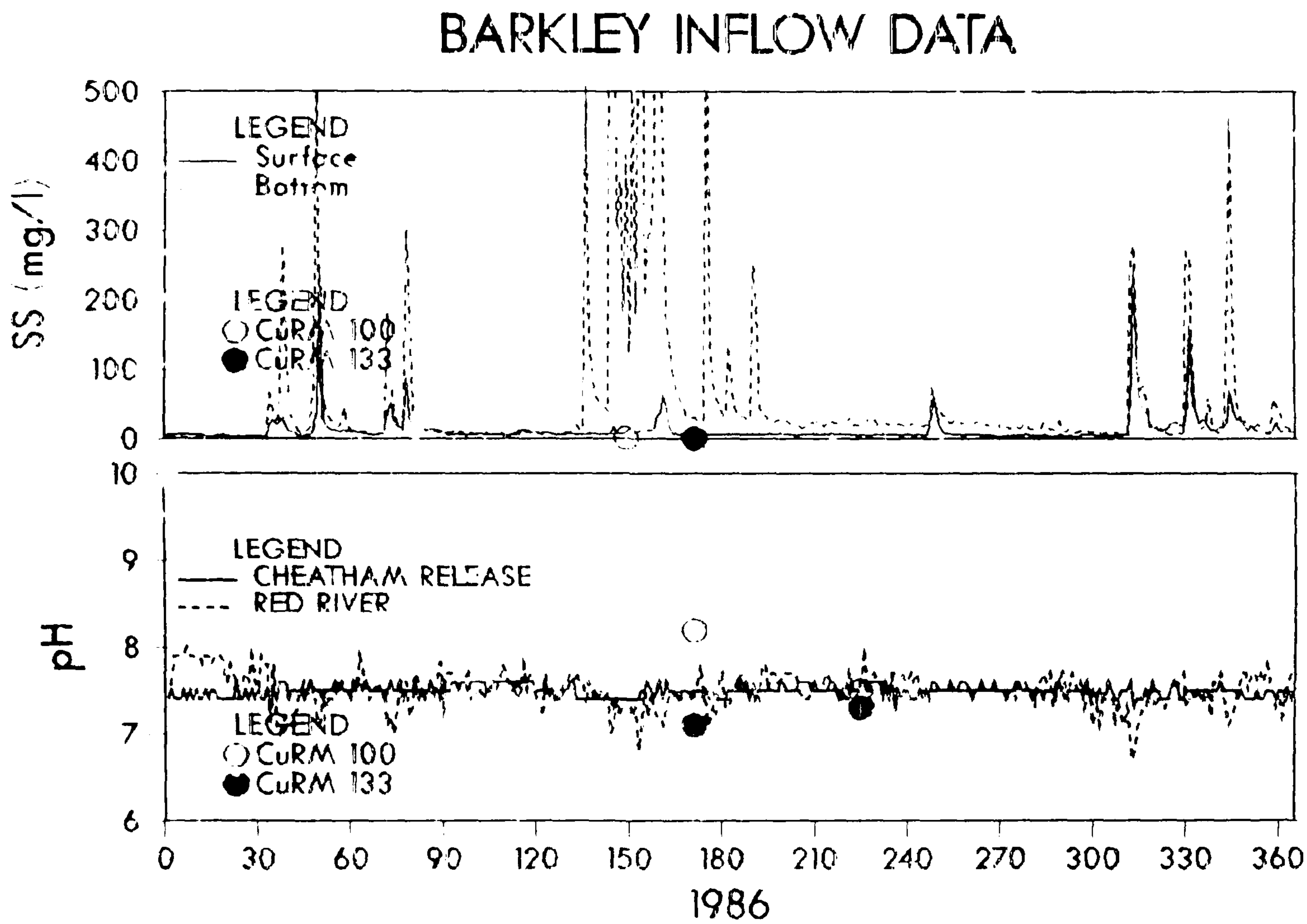


Figure 12 (continued)

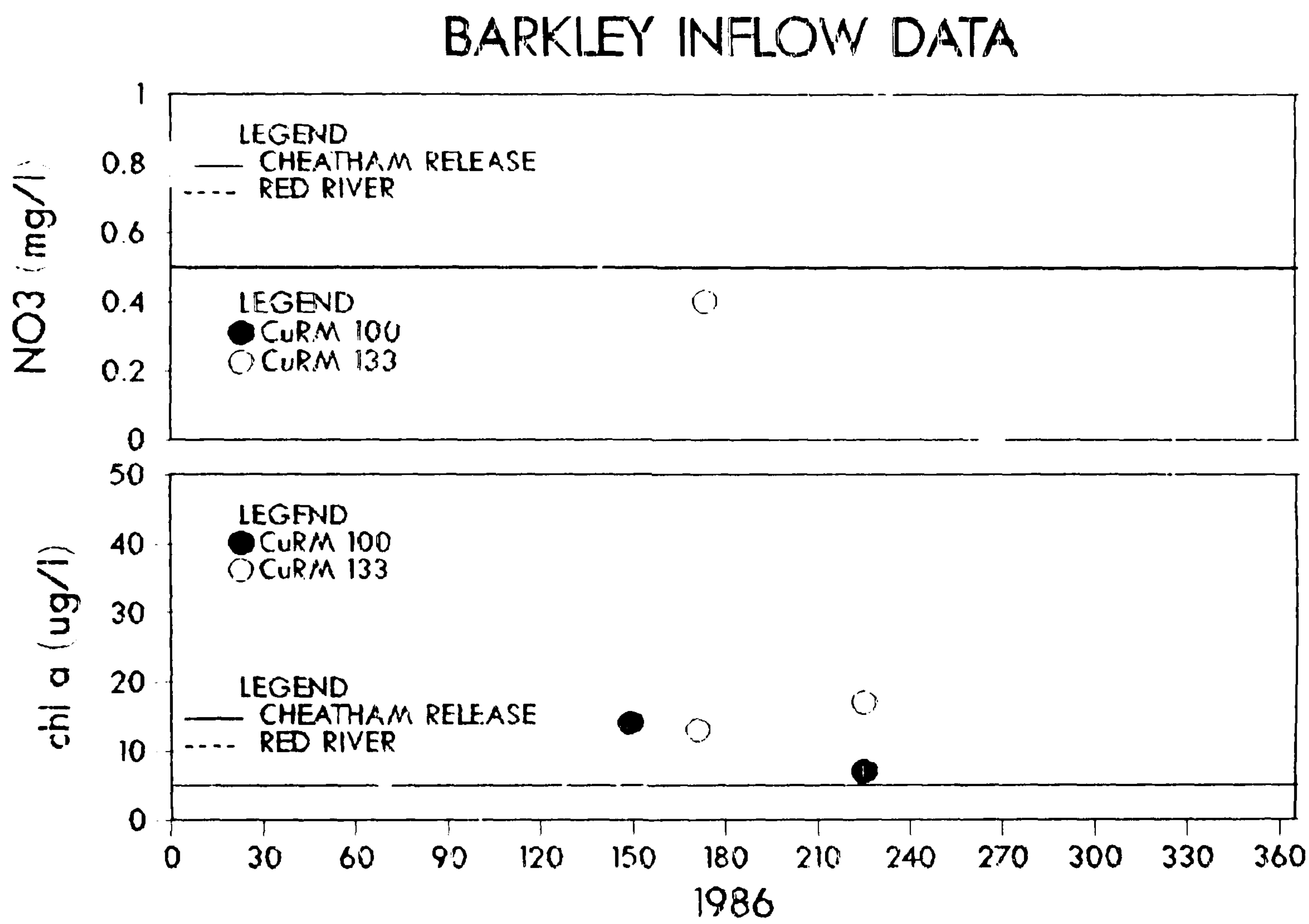


Figure 12 (continued)

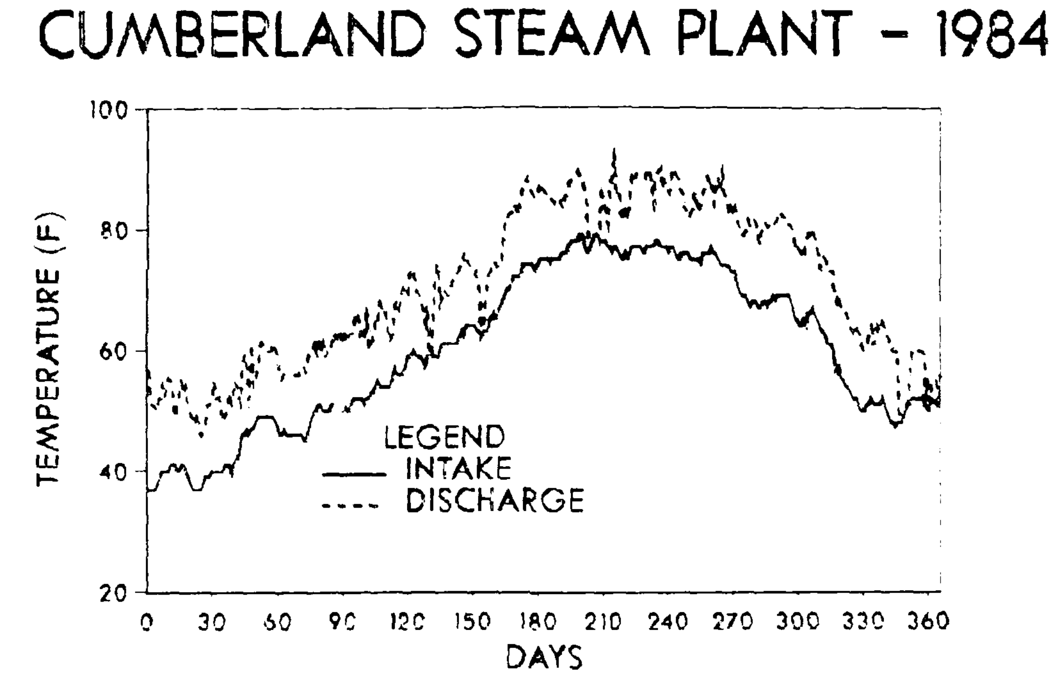
Meteorological Data

Daily average meteorological data were obtained from National Weather Service records taken at the Paducah airport. The model requires drybulb, dewpoint, windspeed, and solar radiation values. The solar radiation values were estimated from cloud cover values. These daily average data were adequate for simulating the dominant seasonal patterns, including the effects of major storm events which often cause cooling from decreased air temperatures, and mixing from higher windspeeds. Local meteorological conditions are recorded at the Cumberland Steam Plant, and might be utilized in future applications.

Cumberland Steam Plant Operations

The Cumberland Steam Plant, a major coal-fired electrical generating plant operated by the Tennessee Valley Authority (TVA), is located in the upstream portion of the reservoir near CuRM 103. The rated capacity of the two-unit plant is 2600 MWe and requires a cooling water flow of 4220 cfs (2727 mgd). The heat from the steam condensers at these design capacity conditions corresponds to a temperature rise of 12° F (6.7° C). The near field effects of this thermal discharge have been studied by TVA (1974).

The daily average operating conditions for 1984-1986 were obtained from the Cumberland Steam Plant superintendent and are shown in Figure 13 for 1984-1986. The intake temperatures were measured, while the heated discharge temperatures were calculated based on the thermal load and cooling water flow rate. The change in cooling water discharge temperature remained fairly constant during 1984, except for several brief shutdown periods. Only one unit operated during the fall, but the temperature rise of the cooling water was similar, since



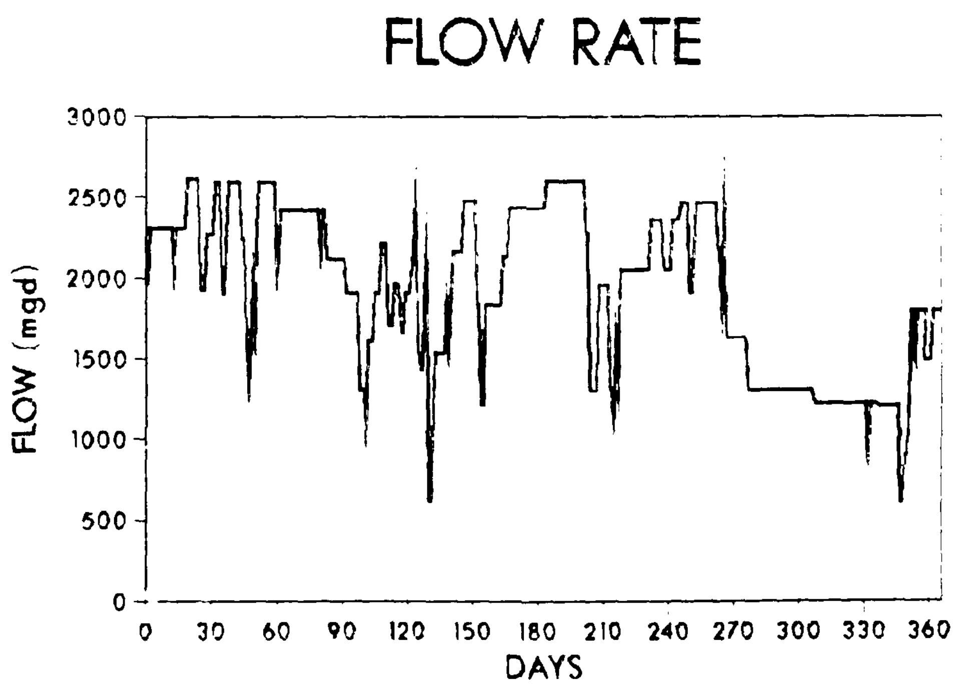
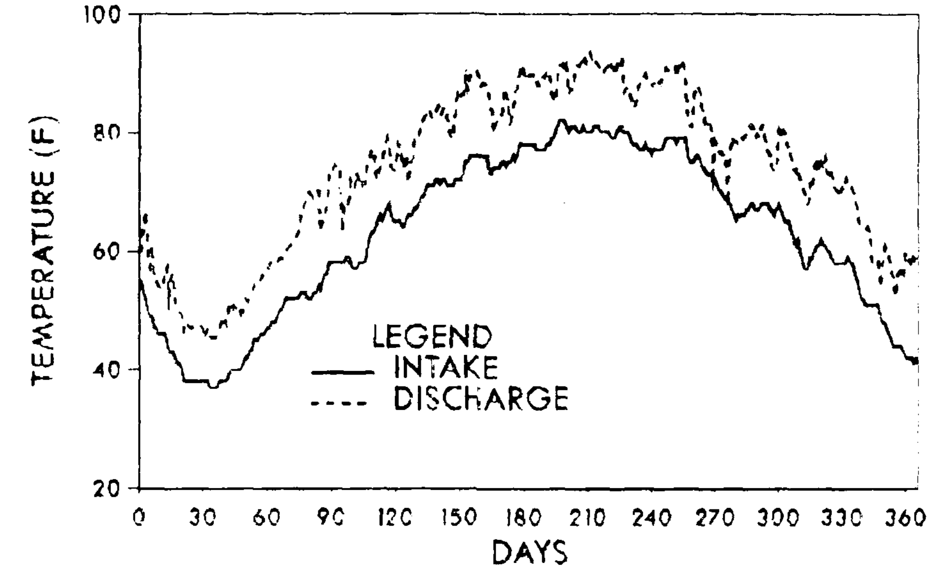


Figure 13 Cumberland Steam Plant Operating Conditions for 1984-86

CUMBERLAND STEAM PLANT - 1985



FLOW RATE

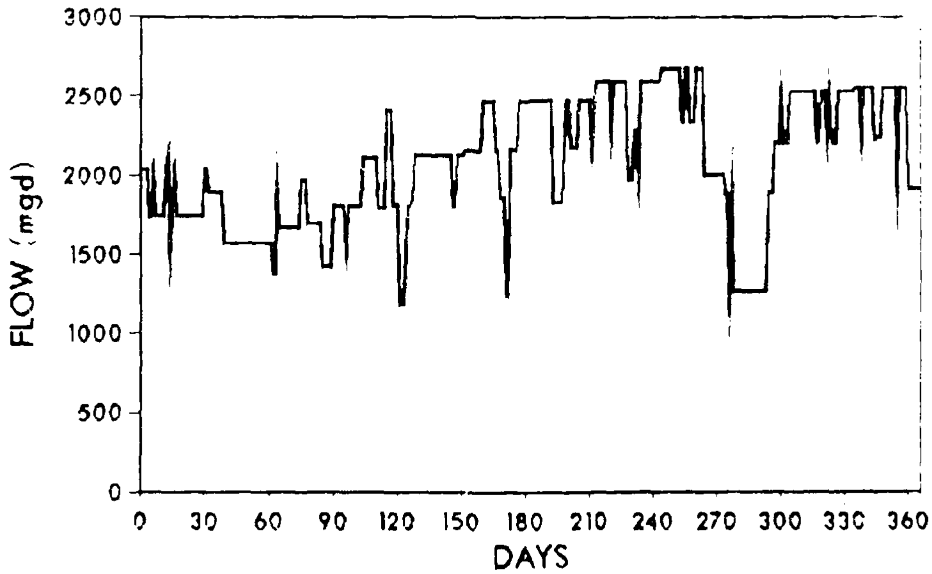
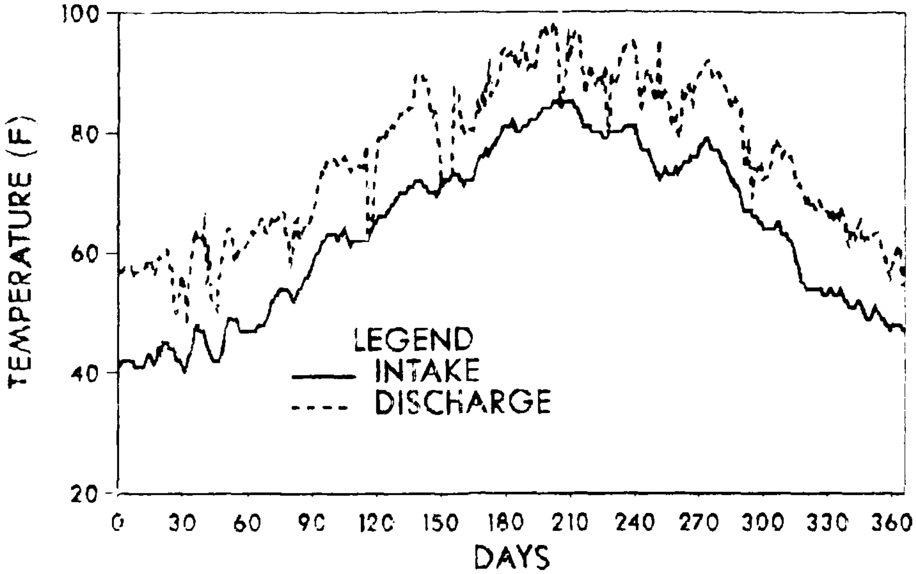


Figure 13 (continued)

CUMBERLAND STEAM PLANT - 1986



FLOW RATE

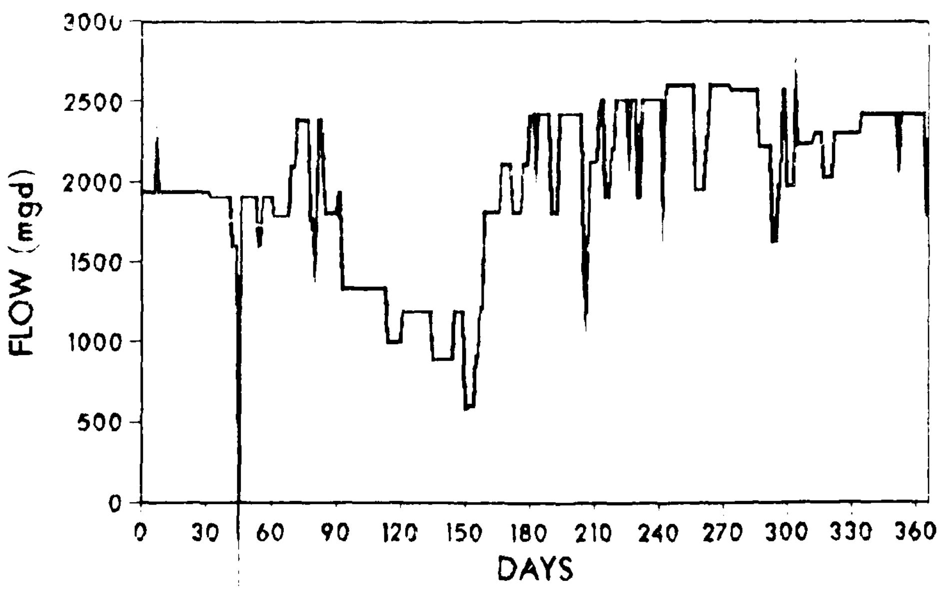


Figure 13 (continued)

the cooling water flow rate was decreased. Operations during 1985 were very constant, with two units producing power all year. Operations were again consistent during 1986, but the effects of the low river flows can be seen in the higher intake and discharge temperatures. Maximum discharge temperatures approached 100° F (38° C) during 1986.

CALIBRATION OF BRANCHED BETTER MODEL TO OBSERVED BARKLEY CONDITIONS

Field data were collected during portions of three years, so the model was calibrated with one year of data (1984) and validated with data from the remaining two years (1985 and 1986). Data from the summer of 1984 indicated that DO depletion occurred in the main channel stations in the downstream portion of the reservoir, and was stronger (lower DO) in the embayments, with complete DO depletion observed in the Little River embayment. Temperature stratification was similar among these downstream sites, suggesting that the major reason for the differences in DO patterns were longer residence times or stronger DO depletion mechanisms within the embayments. Sediment oxygen demands (SOD) or algal growth and subsequent settling and decay are the most likely processes producing the stronger DO depletion in the embayments. Because all of the stations were intermittently mixed by high flows and/or periods of high winds or surface cooling, the monthly sampling frequency missed several interesting stratification and mixing episodes that were simulated by the model. More frequent sampling at representative stations may be required to further validate the model predictions. Nevertheless, several of the important water quality patterns were approximately represented by the BETTER simulations, including some of the differences observed between main channel and embayment locations.

Available Lake Water Quality Data During 1984

Almost all of the model variables were measured during the field surveys conducted in Barkley Lake during the summer of 1984. Vertical profiles of temperature, DO, pH, and conductivity were measured at seven mainstem and embayment stations (King and Jarrett, 1988) at biweekly intervals between late June and early September (5 surveys). Nutrients, suspended sediment, and chlorophyll were sampled from the surface and bottom. No BOD samples were obtained in the lake.

For calibration purposes, these available data were arranged in computer files with near surface (5 ft. depth) and near bottom measurements of six major modeled variables: temperature, dissolved oxygen, suspended sediment, pH, nitrate, and chlorophyll. Surface and bottom concentrations were chosen to characterize stratification and vertical gradients. Four key stations were chosen for comparison with the model predictions during calibration: CuRM 41.5, upstream of the canal to eliminate any effects from Kentucky reservoir inflows; CuRM 58.2, downstream of the Little River embayment; Little River Mile 3.0; and Eddy Creek Mile 2.2. These stations were chosen to show the downstream conditions in the mainstem and embayment portions of Lake Barkley.

Calibration should involve all variables and locations simultaneously, since they are inter-related in the modeling scheme. However, a general sequence of calibration adjustments was used to simplify the calibration choices: 1) heat exchange, stratification, and mixing processes were adjusted to match the available vertical gradients in temperature and water quality data; 2) dissolved oxygen processes were calibrated next to match the observed depletion and supersaturation patterns; and 3) SS (light), nutrients, and algae processes were adjusted to match available nitrate, pH, and chlorophyll data. Experience has

shown that slight changes in the vertical stratification and mixing will have large effects on both DO and algae patterns. But changing an algae related process can indirectly influence the DO patterns, and may slightly modify the stratification. Calibration is complicated by the fact that several changes in coefficients may produce similar effects. All six variables at the four key stations were examined following each calibration adjustment to achieve an overall match with the available 1984 data.

Temperature Calibration

There were a number of early model runs which identified remaining problems in the branching subroutine changes. One check on the model water and mass balance calculations involved setting the initial dye value and all inflow dye values at 100. The model should then calculate dye values of 100 in all segments throughout the simulation. Once the model was operating properly, an initial calibration run was produced with coefficient values obtained from previous BETTER model applications to Old Hickory and Cheatham Lakes. Calibration plots which compare the field data with the surface and bottom model predictions for the corresponding locations were developed. Plots of two variables are shown on a page, so that three pages are required for each station. This initial simulation produced seasonal water quality patterns that generally corresponded with the vailable data. The stratification and mixing patterns were similar to the data, with some DO depletion and significant algal production. The major problems in matching this initial simulation with the data were: 1) the observed DO depletion in the hypolimnion of the mainstem and embayment stations was greater than simulated, 2) the modeled DO depletion in the embayments was not as different (greater) from the main channel stations as observed, 3) simulated

surface and bottom pH values were too high, and 4) simulated chlorophyll values were not high enough in the late summer. The field surveys began in late June of 1984, while the simulations indicated that significant stratification, DO depletion, and algal activity occurred during April, May and June. These early 1984 water quality patterns cannot be calibrated directly with the available data.

The simulated temperature patterns indicated fairly weak (2-5° C) stratification in the spring and summer, with intermittent mixing events caused by surface cooling. These surface and bottom temperature patterns matched the available data well, as shown in Figures 14 to 17 for the four key stations. The simulations indicated many heating and cooling events between measurement points that cannot be directly calibrated, but the general simulated patterns appeared reasonable. The surface plot of temperatures along the reservoir and the Little River embayment during the year (Figure 18) indicated that there was relatively little longitudinal warming, with inflow temperatures remaining below 25° C, and surface temperatures at the dam remaining below 30° C.

Residence Time Patterns

The model uses a variable, called AGE, to calculate and track the travel times of water moving through the reservoir. Figure 19 shows the surface AGE values for the mainstem and Little River embayment during 1984. The AGE patterns are contoured in 10 day increments; the residence time for the mainstem was about 10 days during the winter and spring, but increased to 30 days during July through September, and decreased to less than 10 days due to high flows in November and December. This modeled AGE pattern can be roughly calibrated in comparison to the overall water budget residence time calculations (shown in

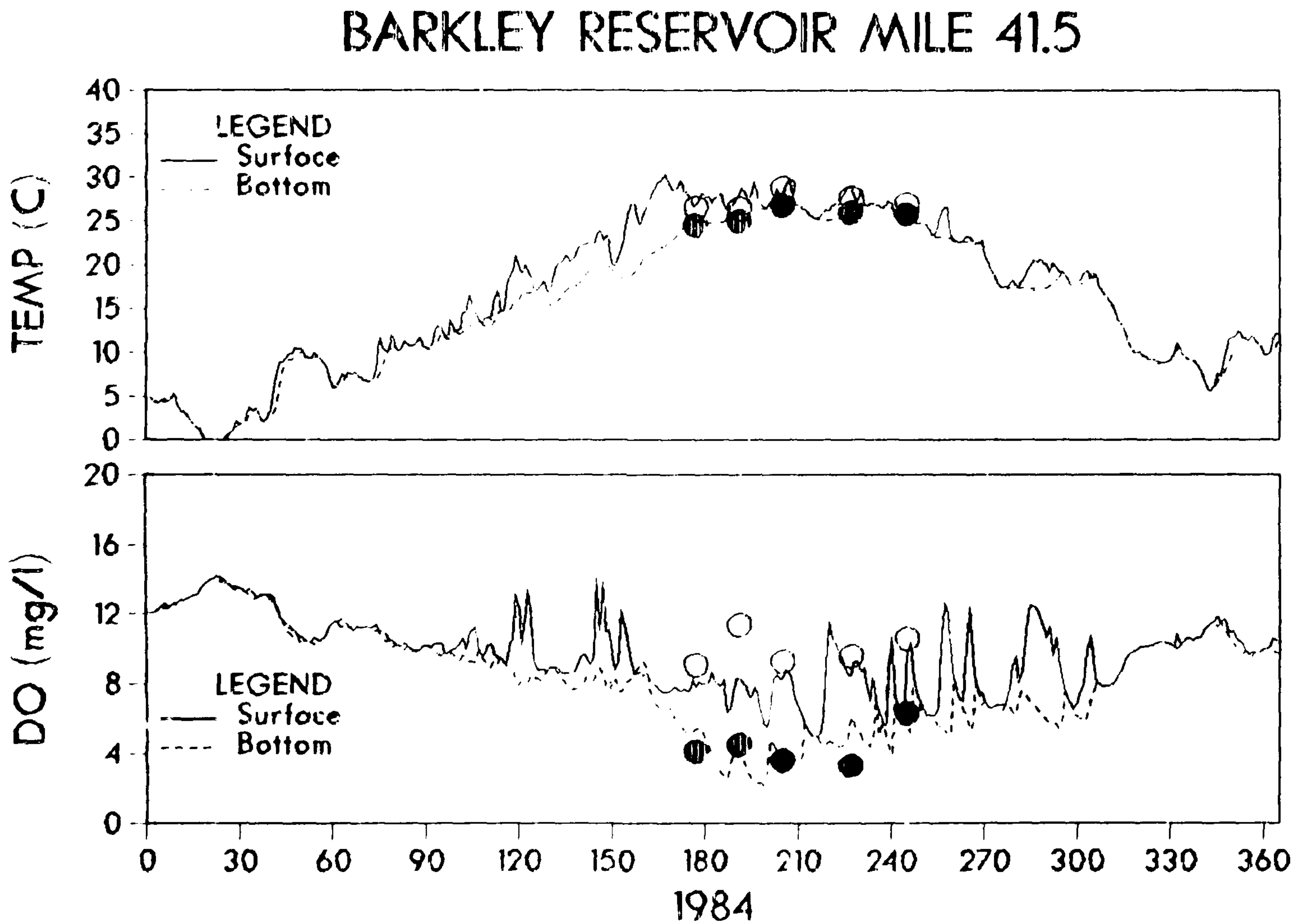


Figure 14 Calibration Results at CuRM 41.5 for 1984

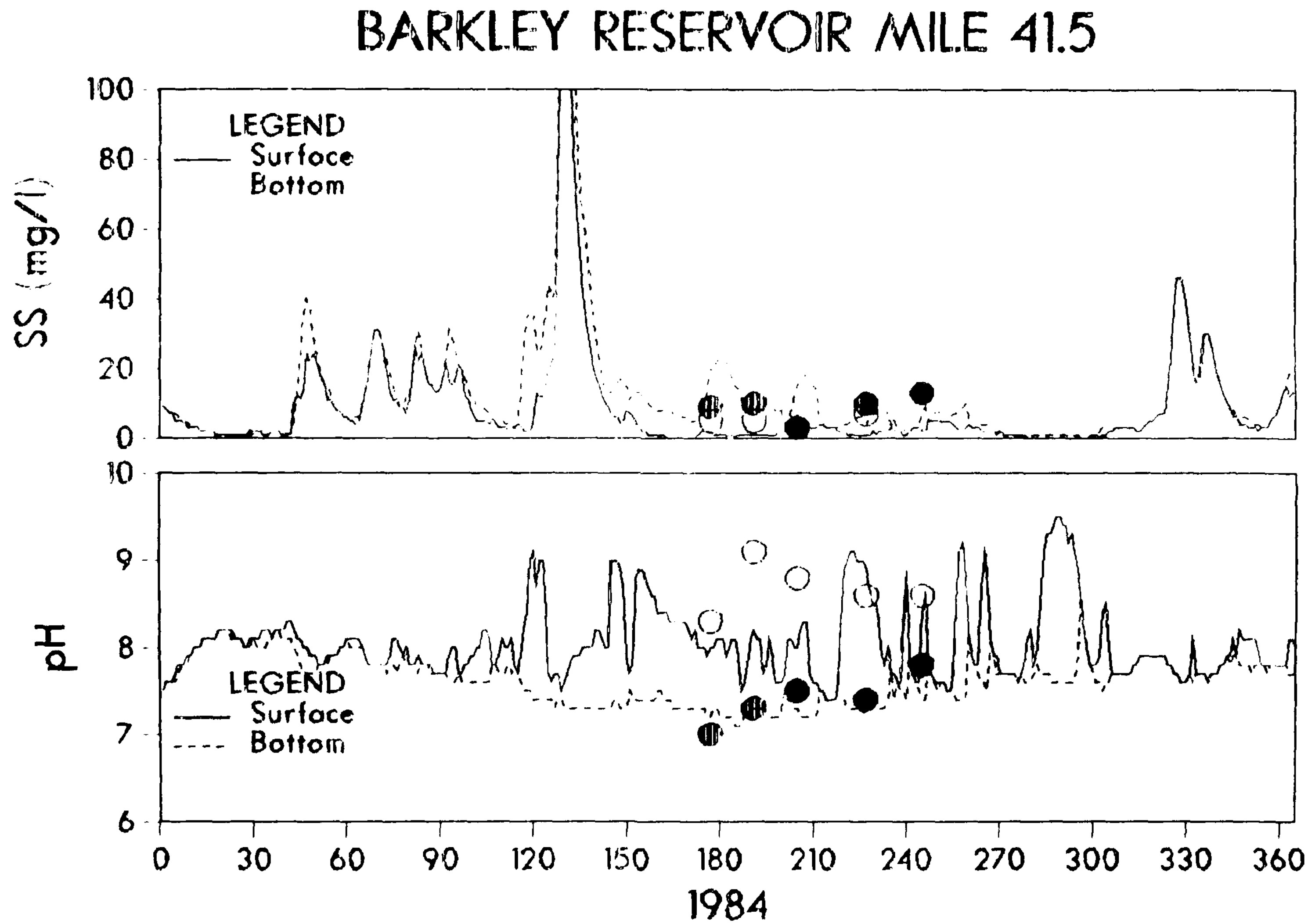


Figure 14 (continued)

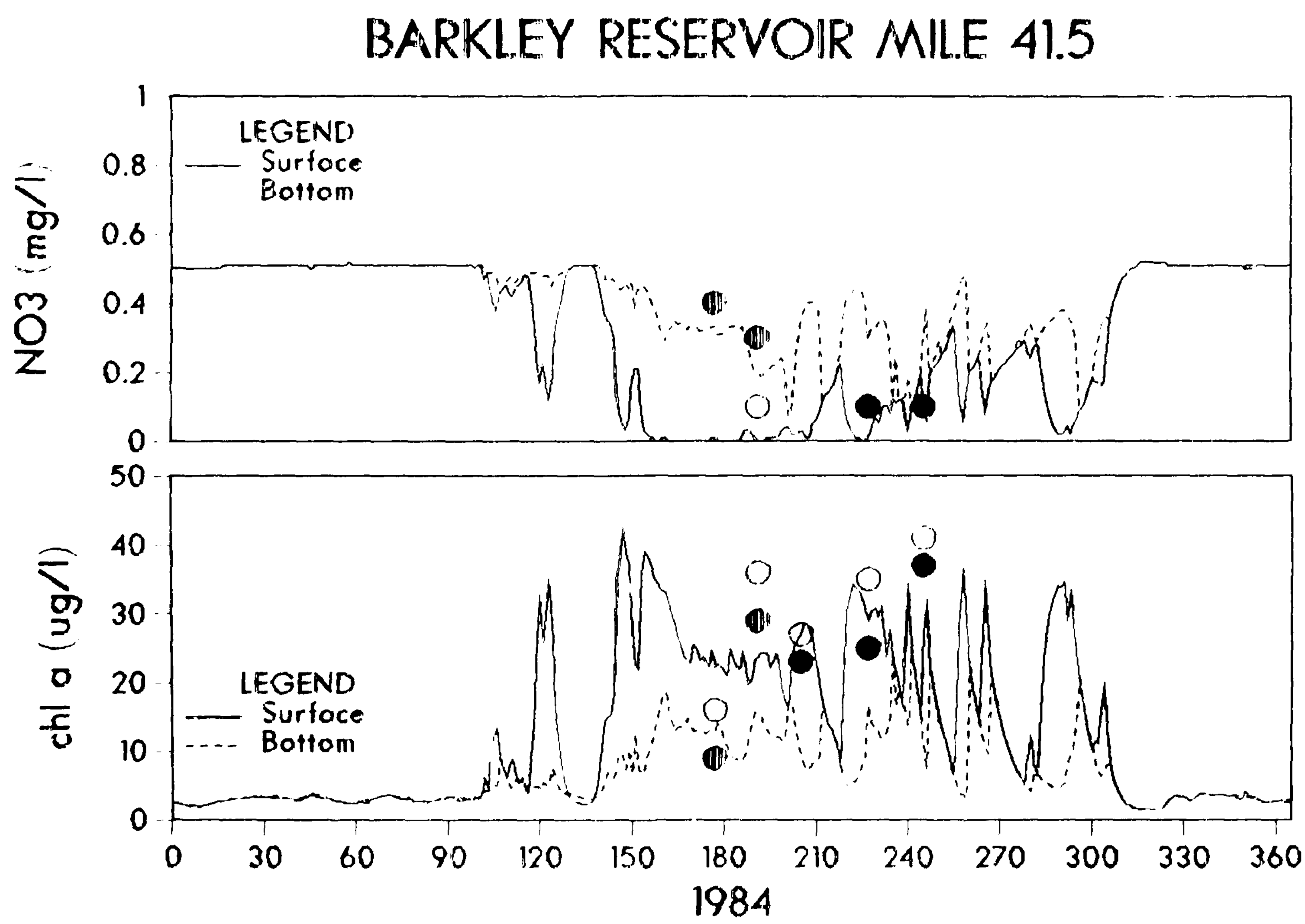


Figure 14 (continued)

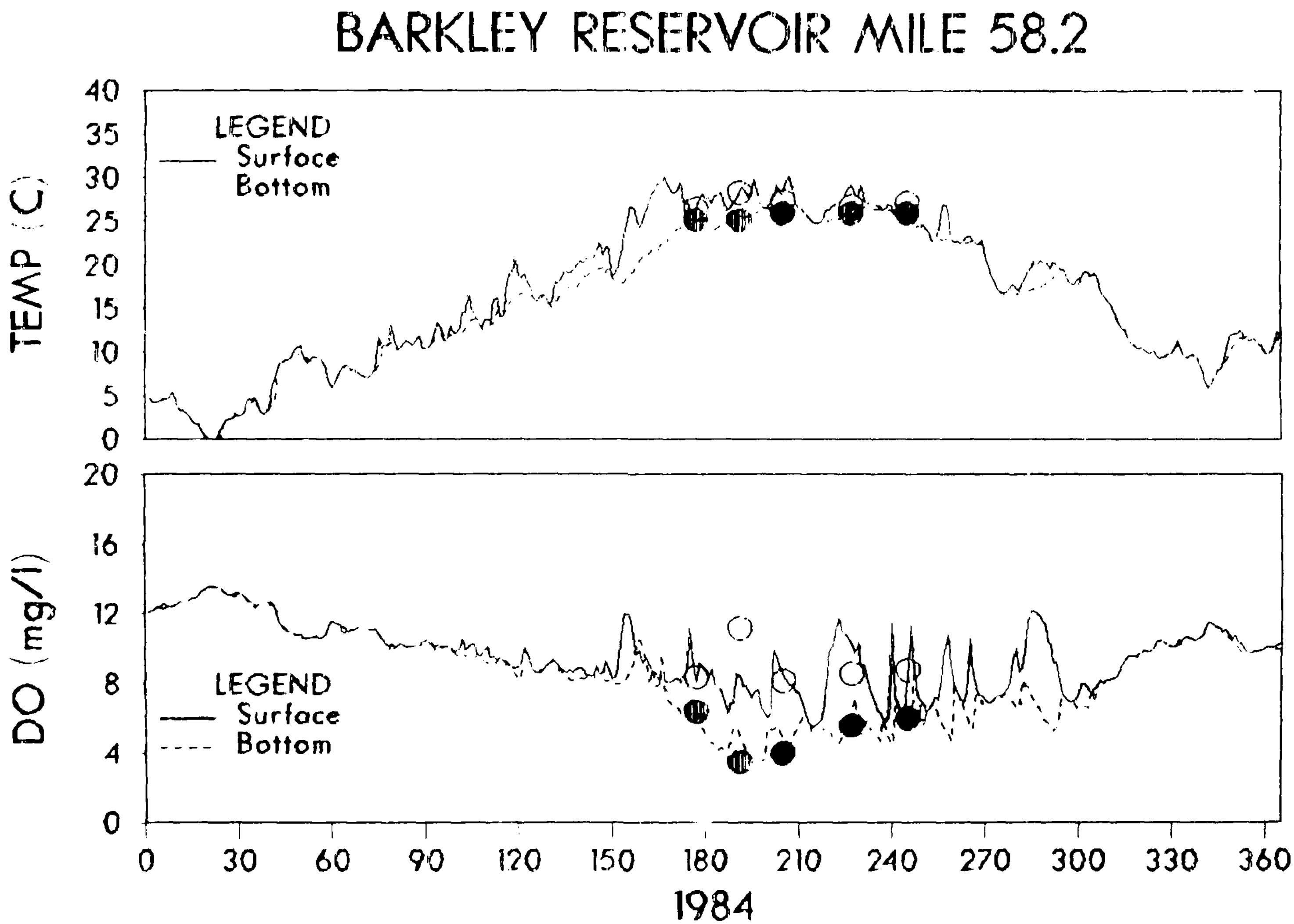
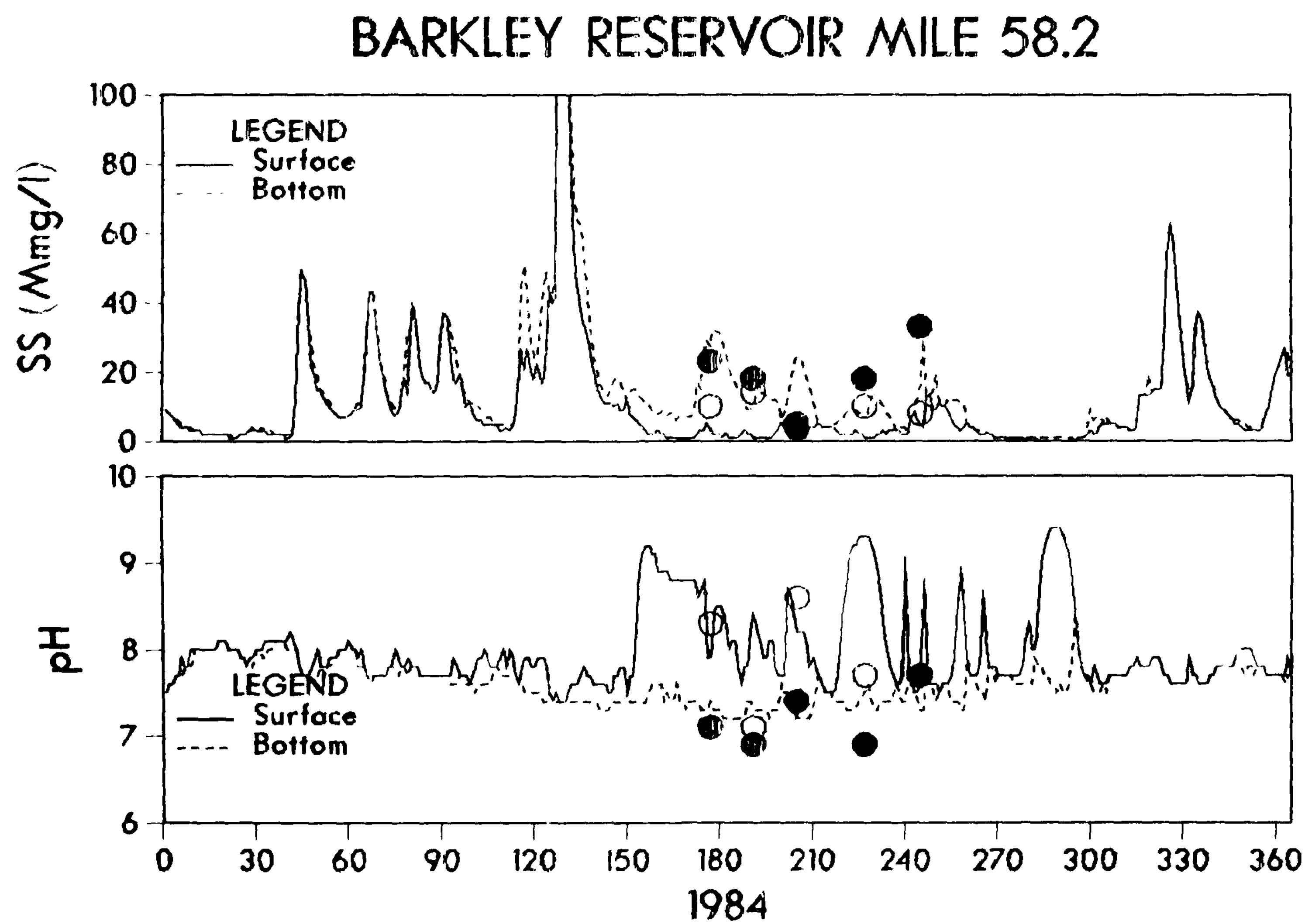


Figure 15 Calibration Results at CuRM 58.2 for 1984



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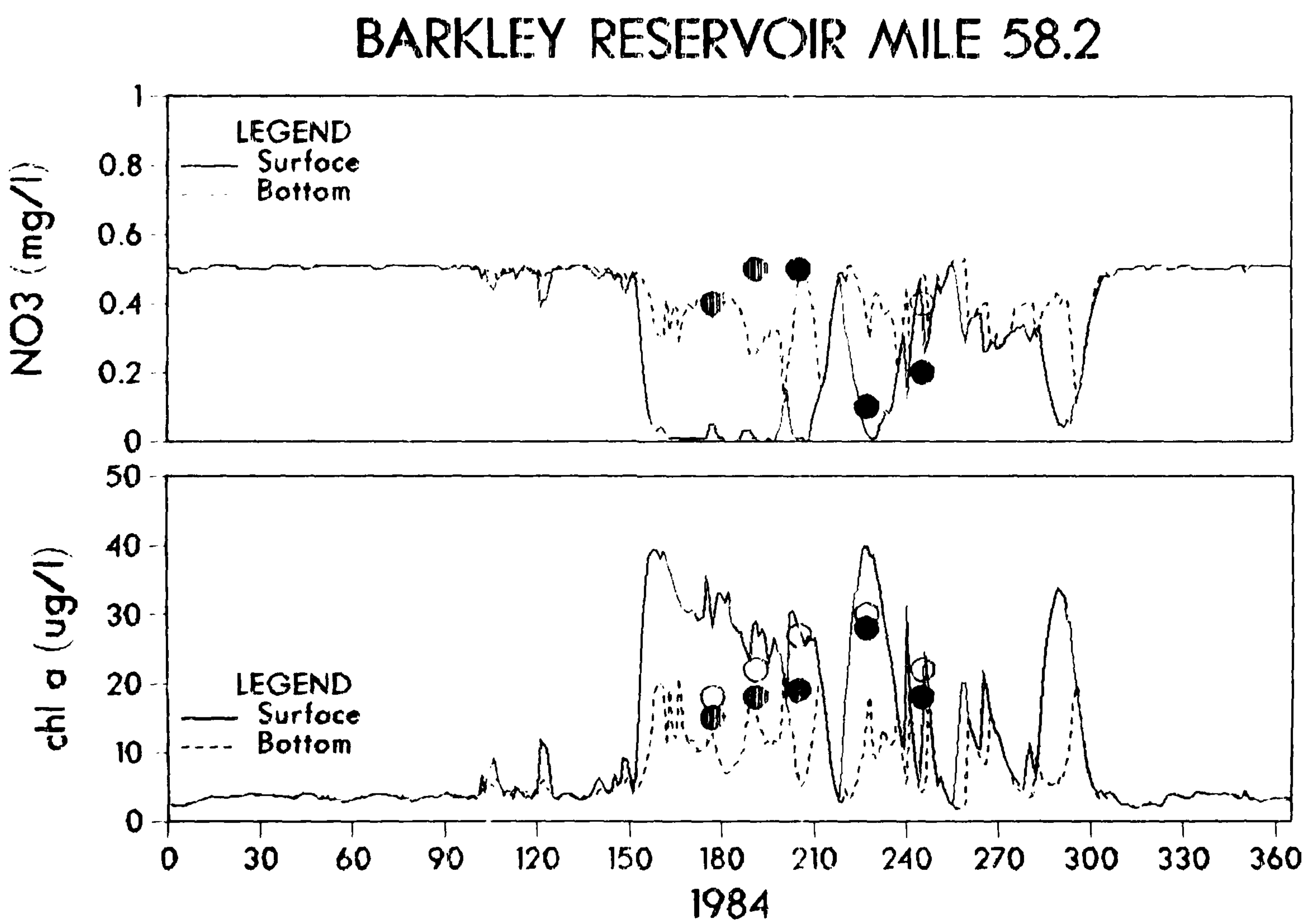

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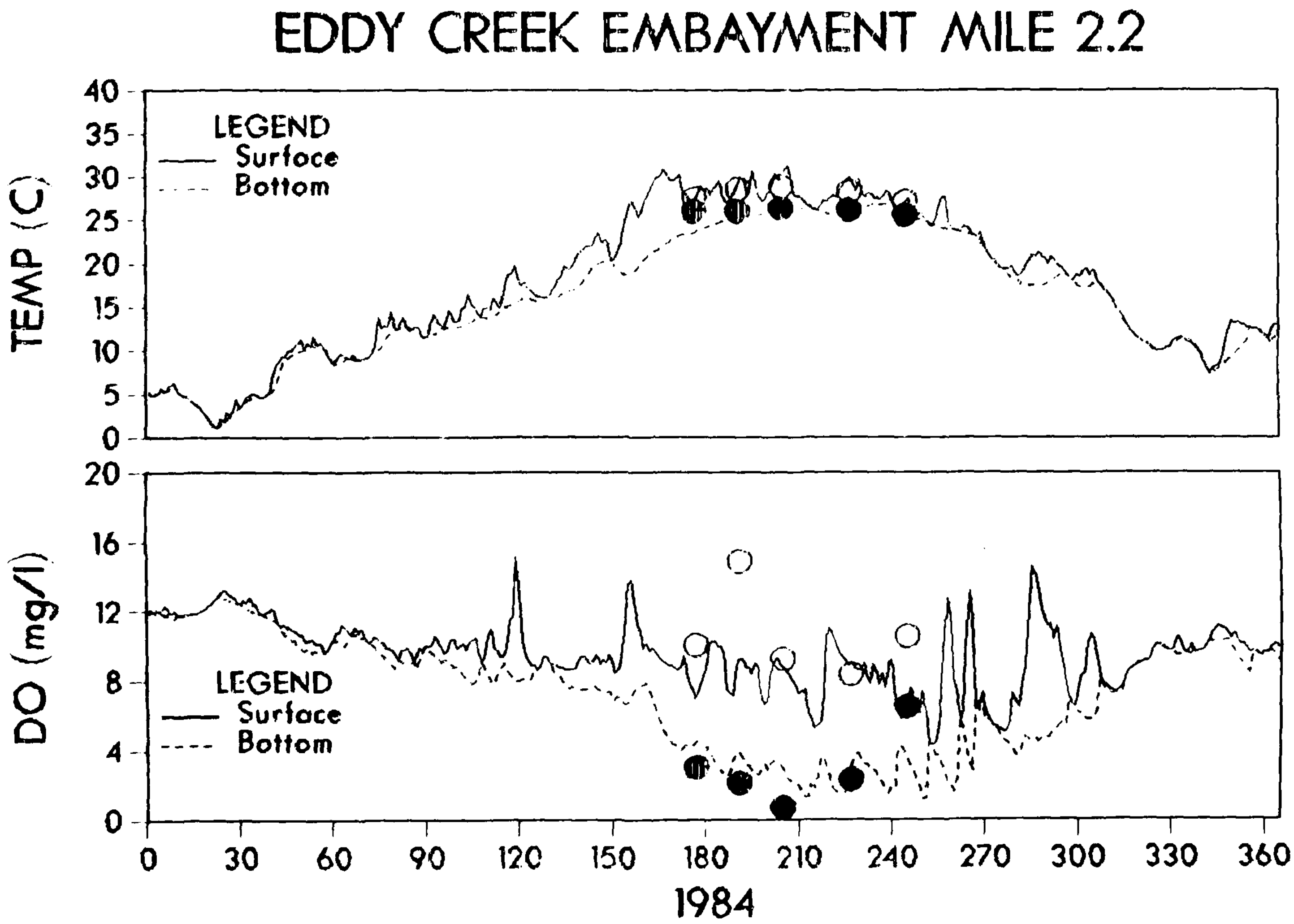
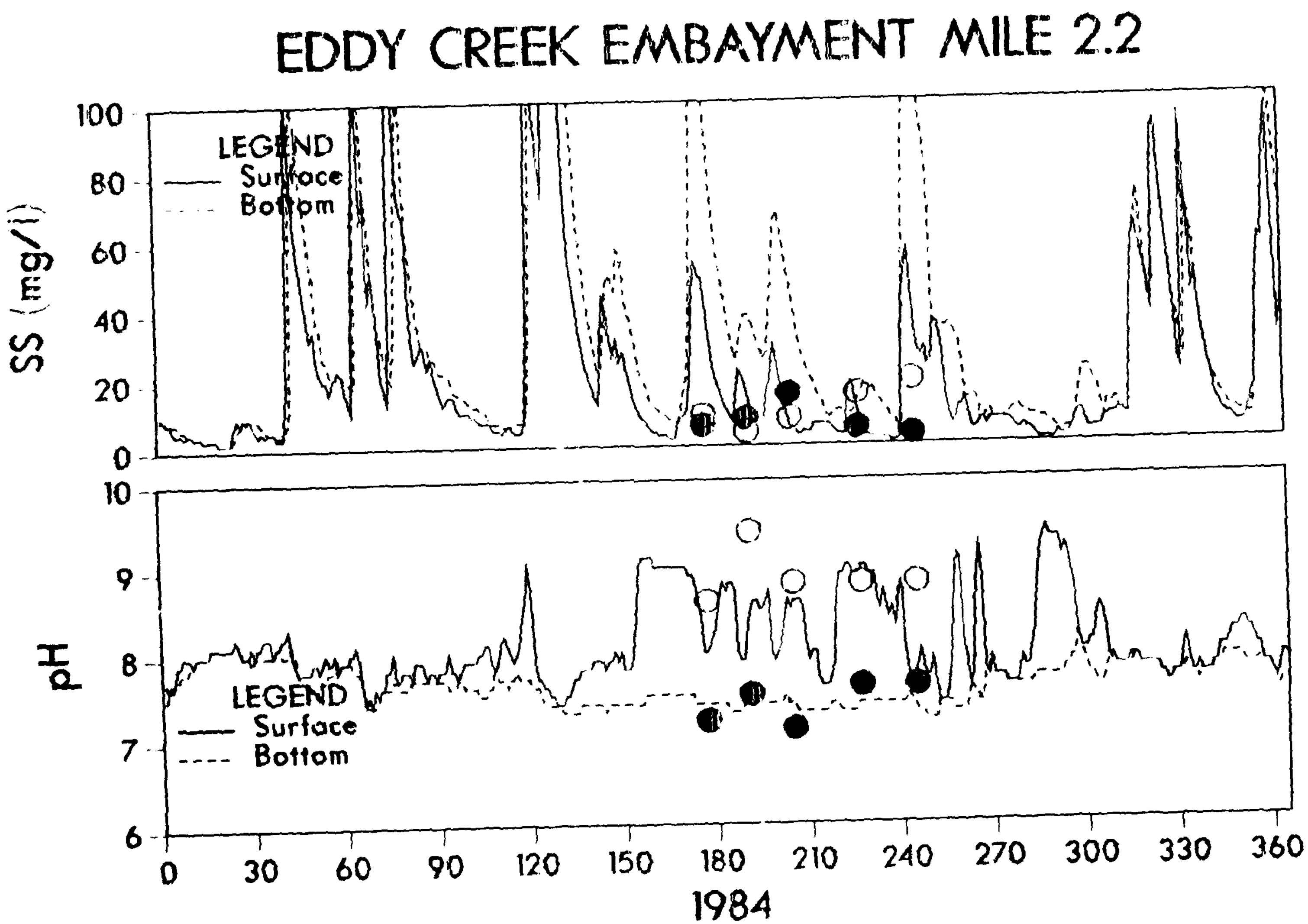


Figure 16 Calibration Results at Eddy Creek Mile 2.2 for 1984



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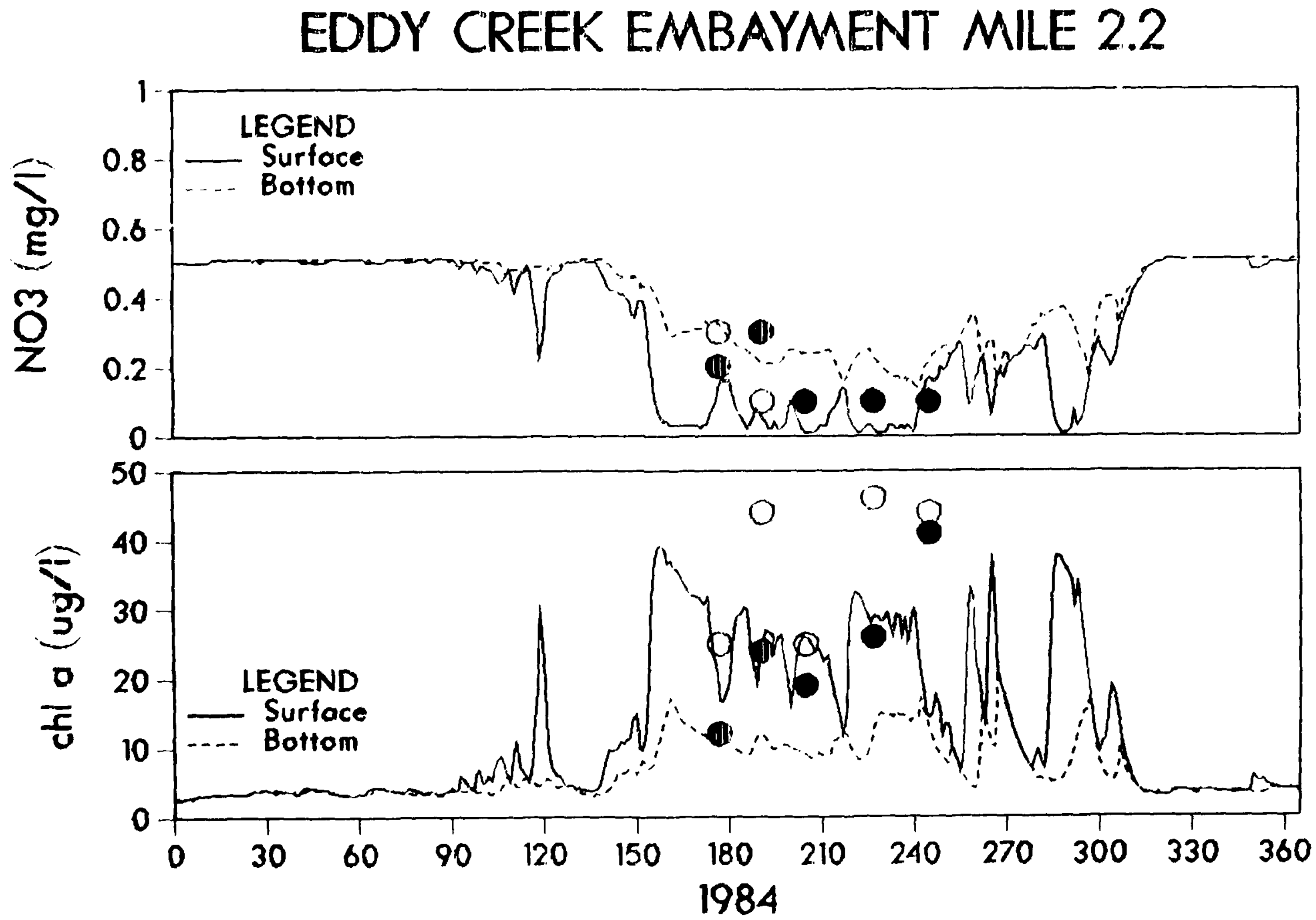

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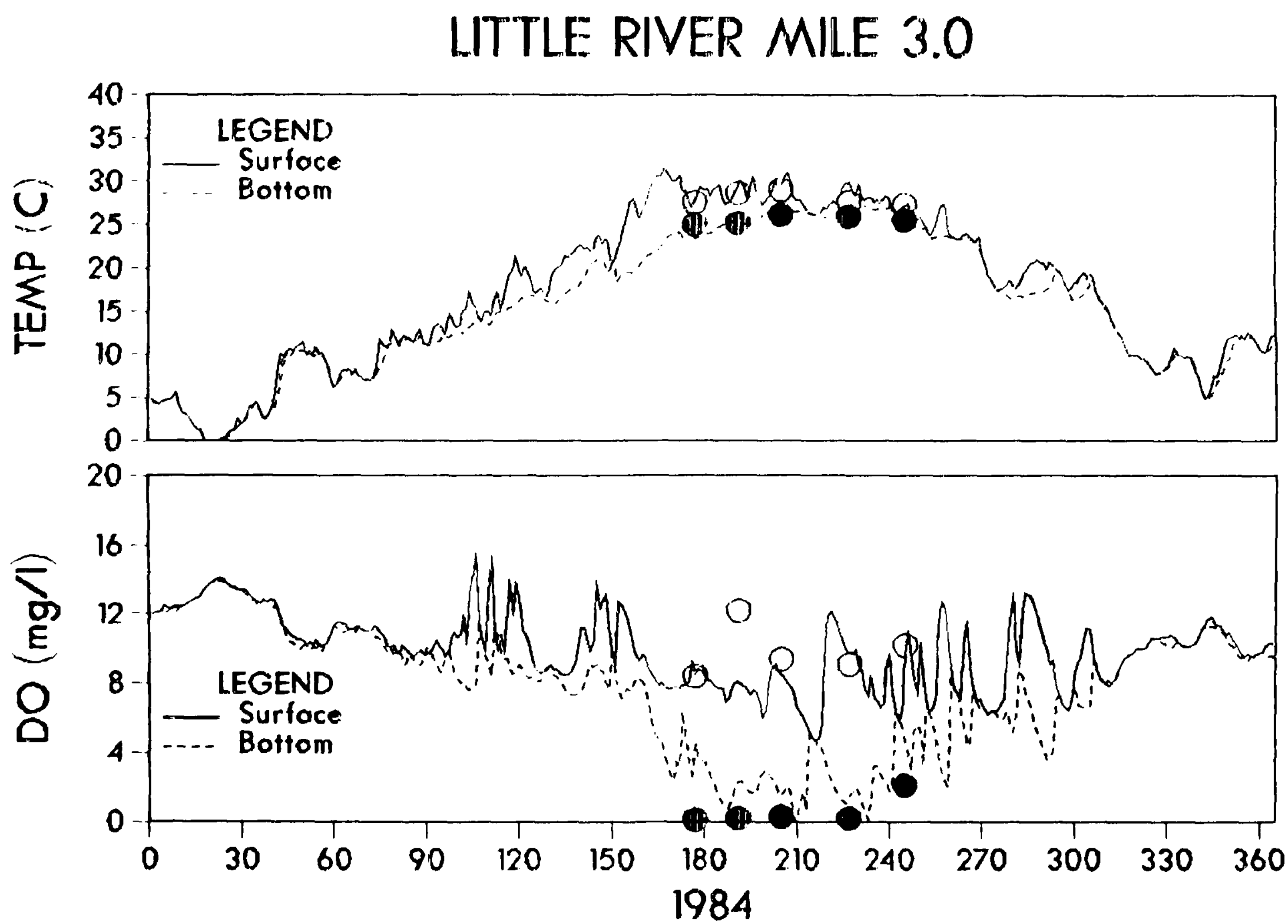
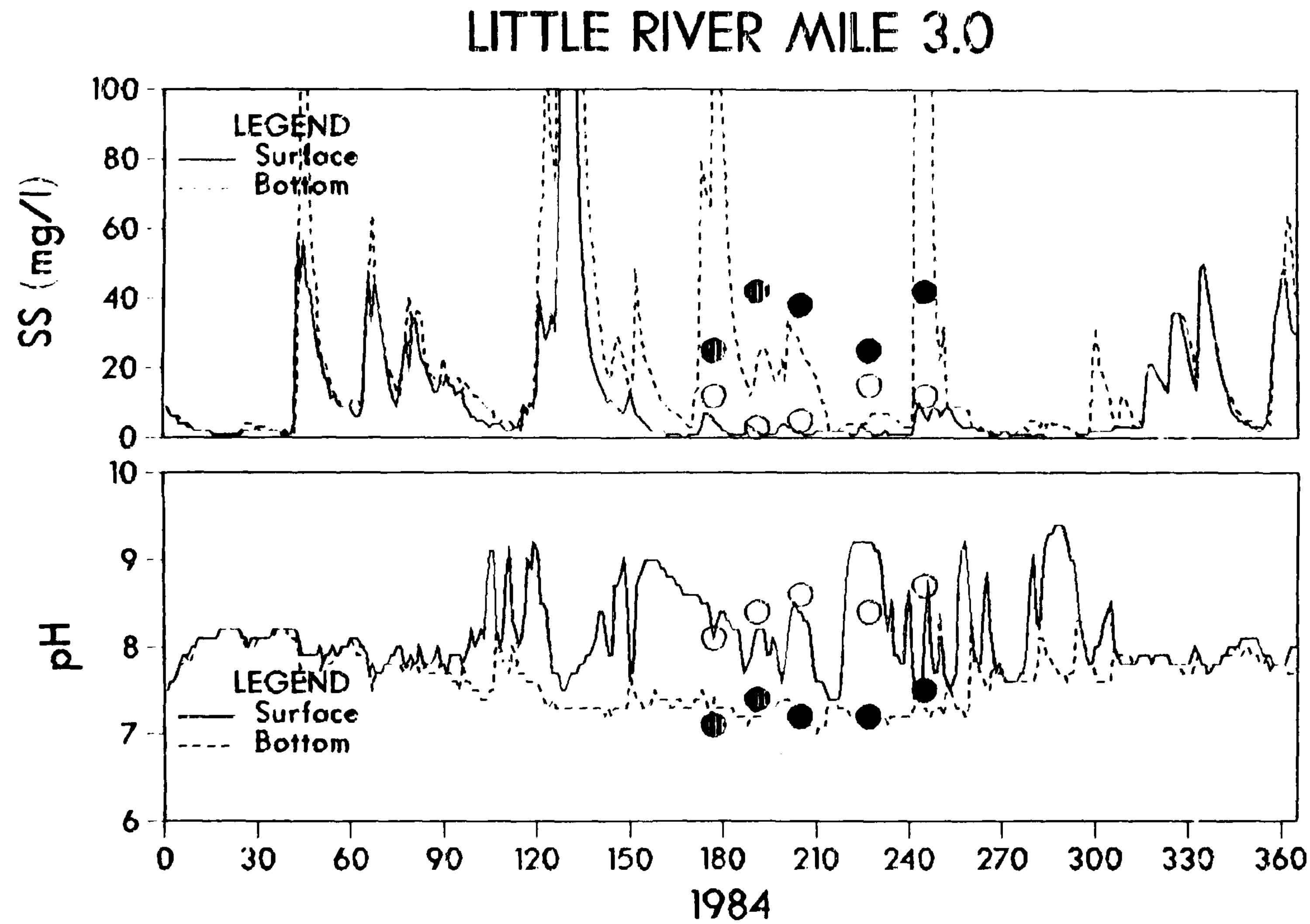


Figure 17 Calibration Results at Little River Mile 3.0 for 1984



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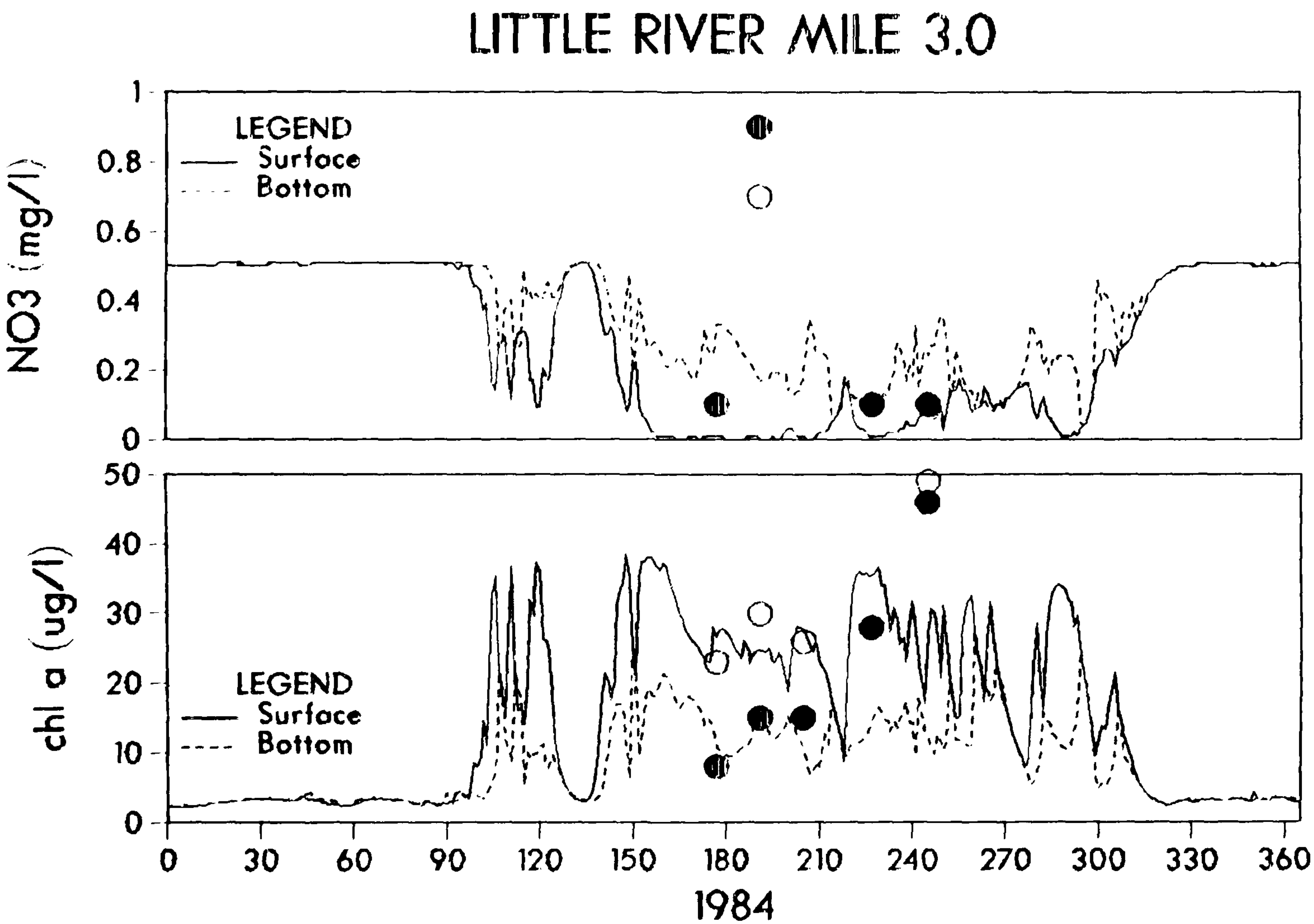


Figure 17 (continued)

Figure 18 Modeled Surface Temperature Patterns for 1984

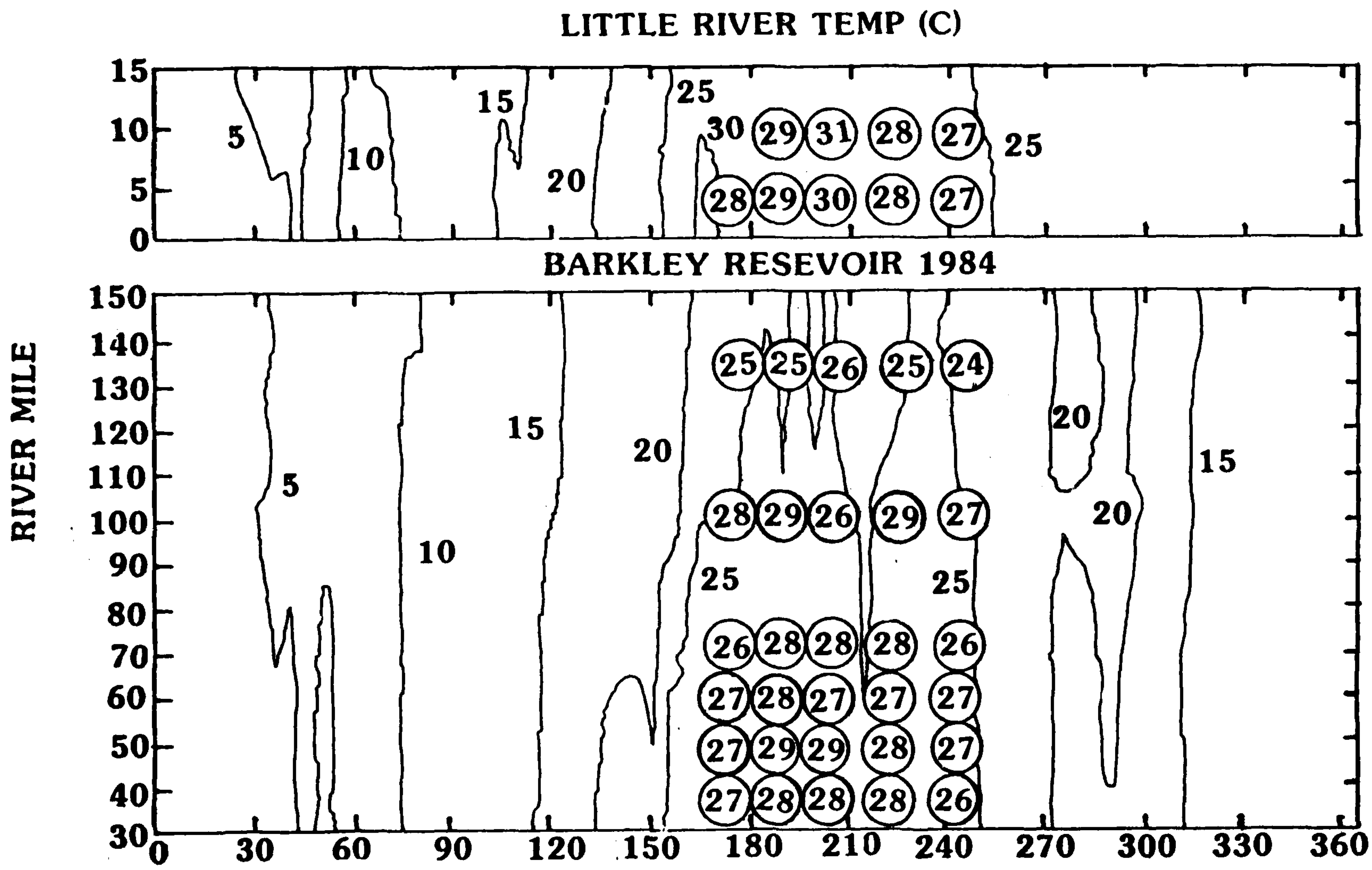


Figure 19 Modeled Surface Residence Time Patterns for 1984

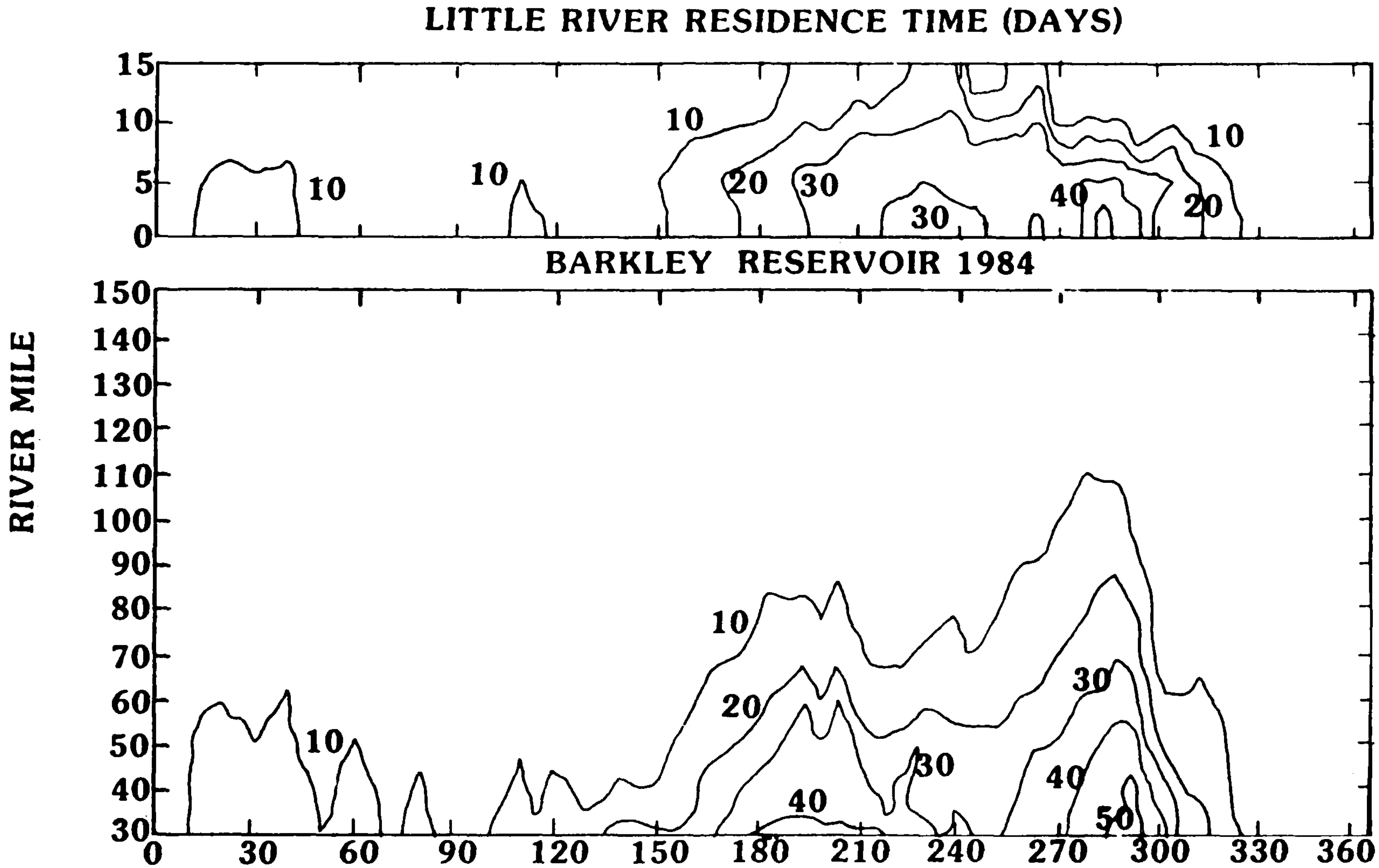


Figure 3). Some differences are expected since the embayment volumes are not included in the mainstem AGE simulations, and inflows and outflows from the Barkley-Kentucky canal were not considered in the water budget calculations. The surface AGE patterns were longer than the average residence time patterns, since surface water is somewhat isolated from the main channel flows during stratified periods. The maximum of 35 days simulated in July was 15 days longer than the average residence time of 20 days calculated from the water budget; the maximum of 50 days in late October was 20 days longer than the average of 35 days calculated from the water budget.

The simulated AGE patterns for the Little River embayment followed a similar pattern as the mainstem, reflecting a similar seasonal inflow sequence and an embayment volume that was proportional to the Little River inflows. The surface AGE values were 5-10 days in the winter and spring, but increased to between 30 and 40 days during the stratified period. There was also a net movement of main channel surface water into the embayments, which tends to give similar residence times near the mouth of the embayment.

For Little River and Eddy Creek, the differences between mainstem and embayment water quality could not be explained simply by longer residence times. The field data indicated somewhat more stratification in the embayments, but nothing dramatically different from the main channel stations. Nevertheless, the observed DO depletion and chlorophyll values were greater in the embayments.

Dissolved Oxygen Calibration

A wind sheltering effect was introduced into the model so that each segment has a separate windspeed reduction factor; all main channel columns have a shelter coefficient of 1.0, while the embayment segments were given a shelter

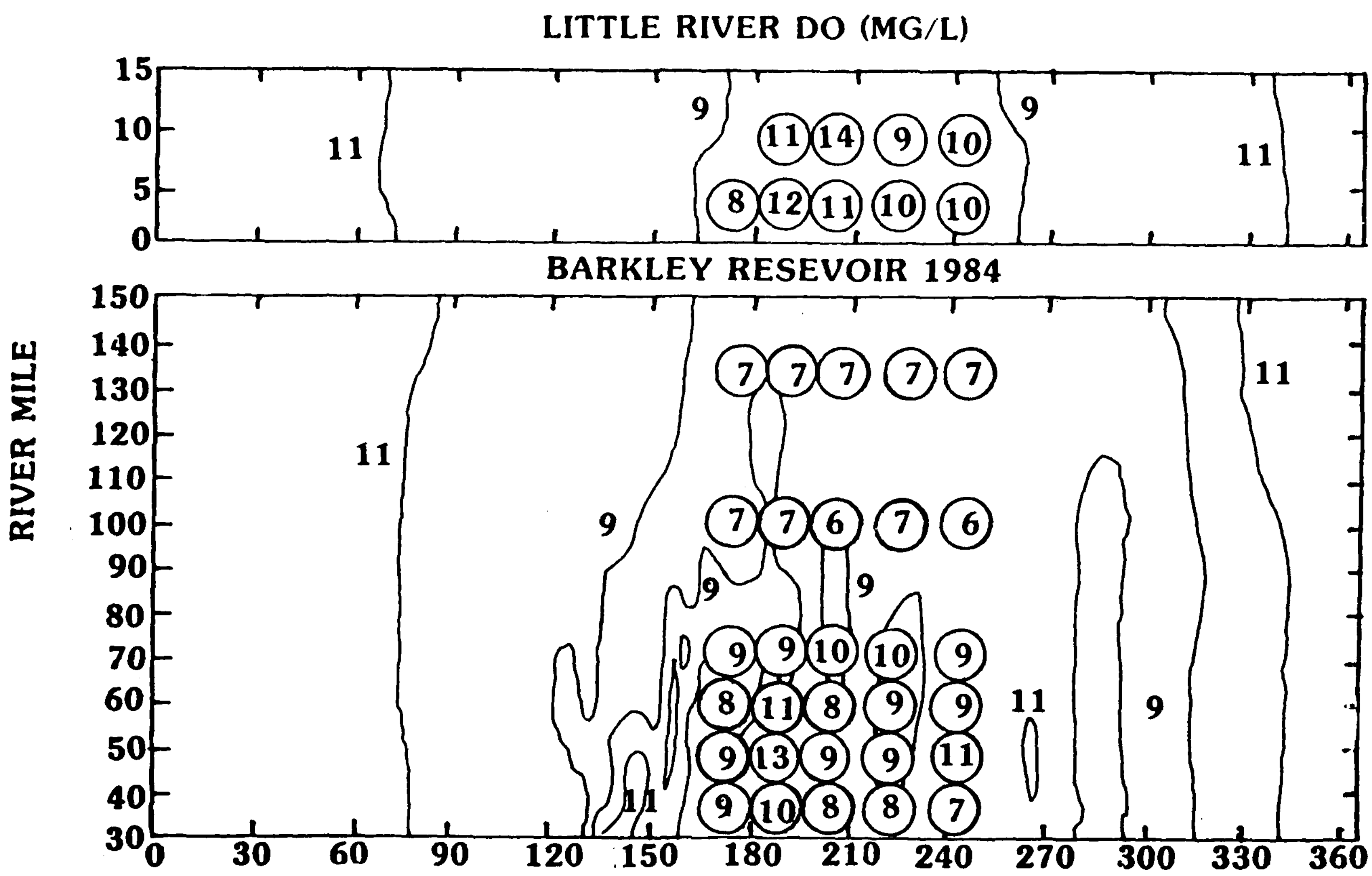
coefficient of 0.75. This allowed the surface temperatures of the embayments to increase due to reduced evaporation, and reduced the wind mixing. The net effect was that the embayments remained stratified more of the time, and the modeled DO depletion was stronger. The embayment bottom DO concentrations still were not as low as the field data indicated, so the SOD rates were increased for the embayment segments to 0.5 g-O_2/m^2-day which was twice the initial main channel values of 0.25 g-O_2/m^2-day. This still did not produce enough DO depletion, so all of the SOD rates were increased. The main channel segments were set at 1.0 and the embayment segments were set at 1.5 g-O_2/m^2-day. The resulting calibrated DO patterns are shown in Figures 14 to 17. The modeled DO patterns for 1984 better matched the available summer measurements in both the main channel and embayments, although the modeled embayment DO patterns included intermittent mixing events which kept the bottom DO concentration higher than observed. Continuous monitoring of temperature and DO in the surface and bottom of key stations will be required to calibrate these intermittent mixing and stratification events.

The surface DO patterns, shown in Figure 20, indicate that there were some patches of supersaturated DO concentrations during the summer, corresponding to rapid algal growth conditions. Surface DO was more generally dominated by saturation concentrations caused by the relatively strong aeration from wind and flow turbulence.

Suspended Sediment Calibration

The main channel SS measurements were all generally low, which corresponded to the simulated patterns quite well. The major storm inflows having high turbidity values occurred prior to the surveys in 1984. The tributary inflows

Figure 20 Modeled Surface DO Patterns for 1984



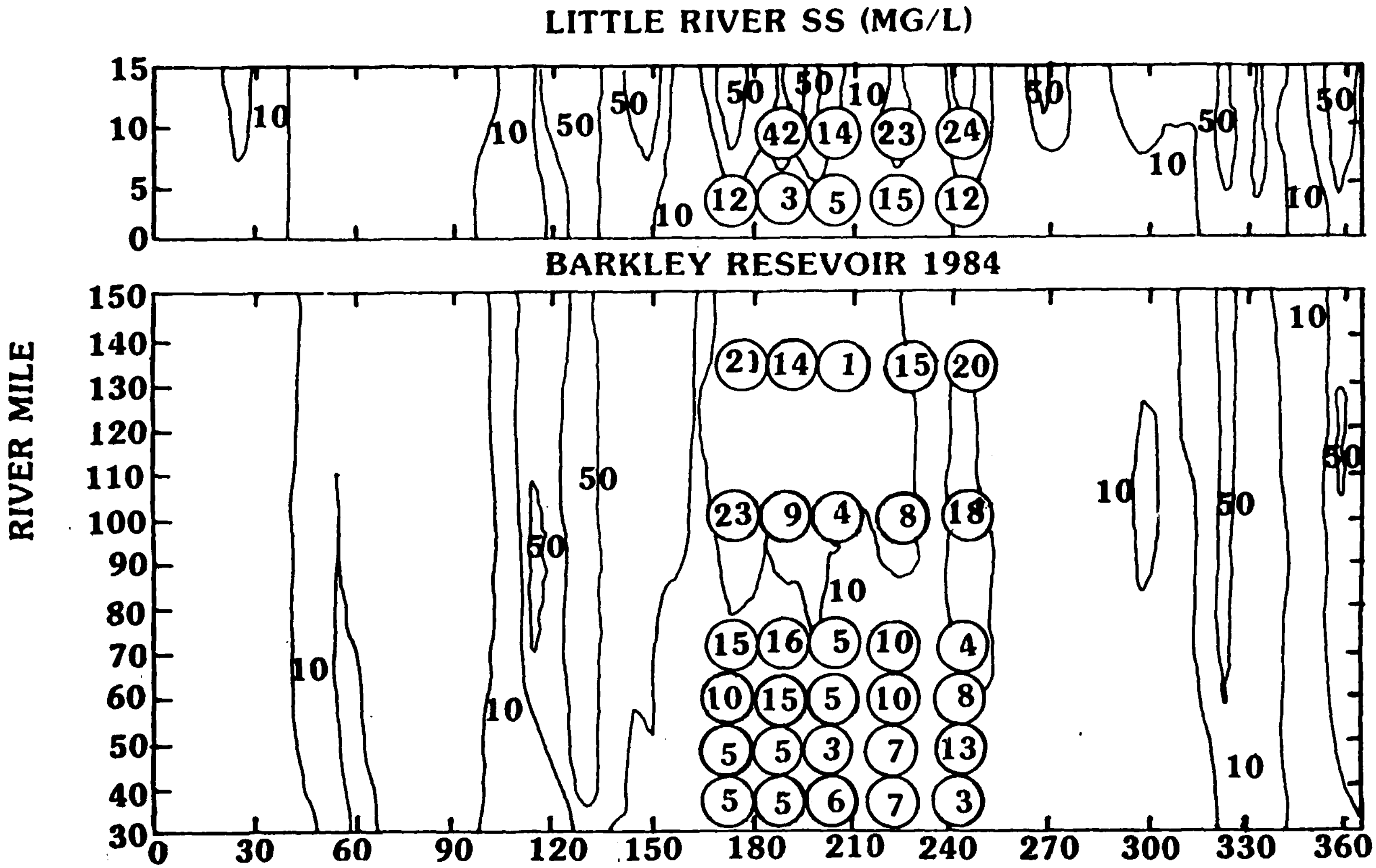
to Little River and Eddy Creek had high turbidity (based on Red River measurements at Springfield) throughout the summer period, and the field data in these two embayments were generally lower than the simulations. The SS settling rate was increased from 0.3 to 0.5 m/day, and the simulated values in the embayments decreased accordingly. The major source of error is probably the unmeasured inflow turbidity for these two tributary streams. The simulated SS values in Eddy Creek were particularly high, suggesting that the inflow turbidities were much lower than those measured in the Red River. The calibrated SS patterns are shown in Figures 14 to 17 for the four key stations during 1984.

The SS patterns are well illustrated in the surface plot showing the SS concentrations longitudinally in the main channel and Little River embayment through 1984 (Figure 21). High turbidity inflows during major runoff events move into Lake Barkley and block light penetration. Values above 20 mg/L have a significant effect on light. Settling and density deflection of the flows produce lower surface concentrations in downstream segments. Mixing events occasionally increase the surface SS concentrations. The lake remained turbid during most of the winter and spring, with clearer conditions developing by June in the downstream portion of the lake. Most of the lake then remained clear until major storm inflows during late November.

Nitrate, pH, and Chlorophyll Calibration

The pH simulations were generally too high at the surface and bottom. The simulated nitrate uptake and chlorophyll patterns, along with the available data, are shown in Figures 14 to 17. These algae related patterns matched the data fairly well, although the model indicated variability caused by mixing events that cannot be confirmed with the bi-weekly data. The major problem remaining

Figure 21 Modeled Surface SS Patterns for 1984



was the higher than observed pH simulations. Several possible adjustments were tested: 1) an increased algal respiration rate was simulated to increase the amount of CO_2 released into the water, which should lower the pH; 2) an increased half-saturation coefficient for CO_2 was simulated to lower the maximum pH for algal growth; 3) the sediment oxygen demand algorithm was changed to release CO_2 at a rate proportional to SOD; and 4) an increased inflow of organic materials was simulated, which would subsequently release more CO_2 during decay. Both the increased inflow of organic materials (corresponding to a 5-day BOD of 2.5 mg/L rather than 1.5 mg/L as originally specified) and a slight release of CO_2 from the sediment were helpful in matching the observed DO and pH patterns.

The surface plots of pH, nitrate, and chlorophyll are shown in Figures 22 to 24. Because of cool temperatures, vertical mixing, short residence times, and high SS concentrations, algal growth was limited until June. High pH patterns were simulated between the Cumberland Stream Plant and the dam during the summer and fall. These periods of high pH were interrupted by the periodic mixing that occurred during surface cooling episodes. The simulated nitrate uptake patterns were strongest during the periods of low SS concentrations and stable stratification. Nitrate uptake was quite rapid once algal growth conditions became favorable. A region of complete nitrate uptake occurred downstream of CuRM 80 during the summer and fall. Vertical mixing replenished the surface nitrate concentrations and allowed additional algal productivity throughout the fall. The resulting chlorophyll values increased to 30 μg/L in these regions during periods of suitable growth conditions. Once the nutrients

Figure 22 Modeled Surface pH Patterns for 1984

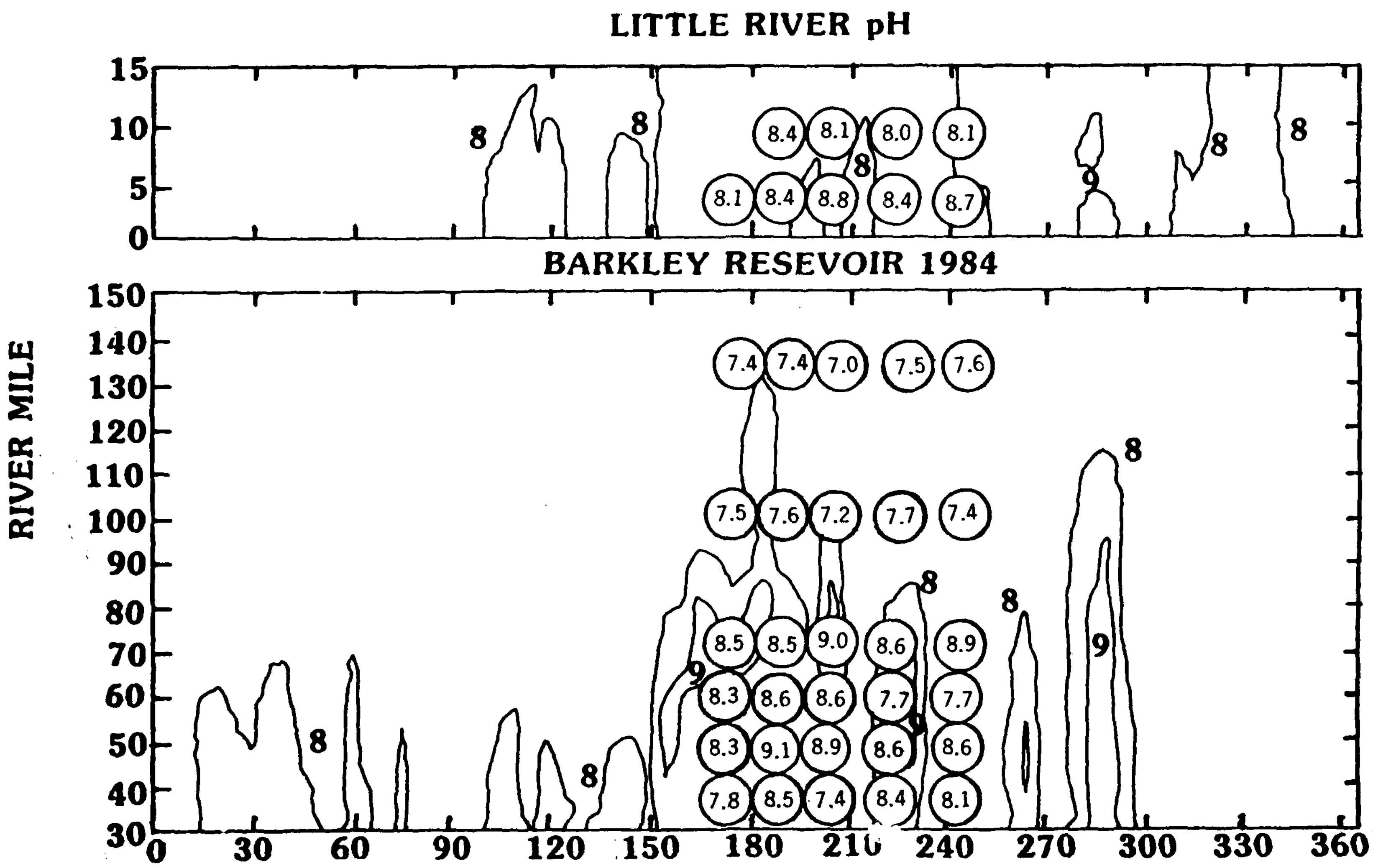


Figure 23 Modeled Surface Nitrate Patterns for 1984

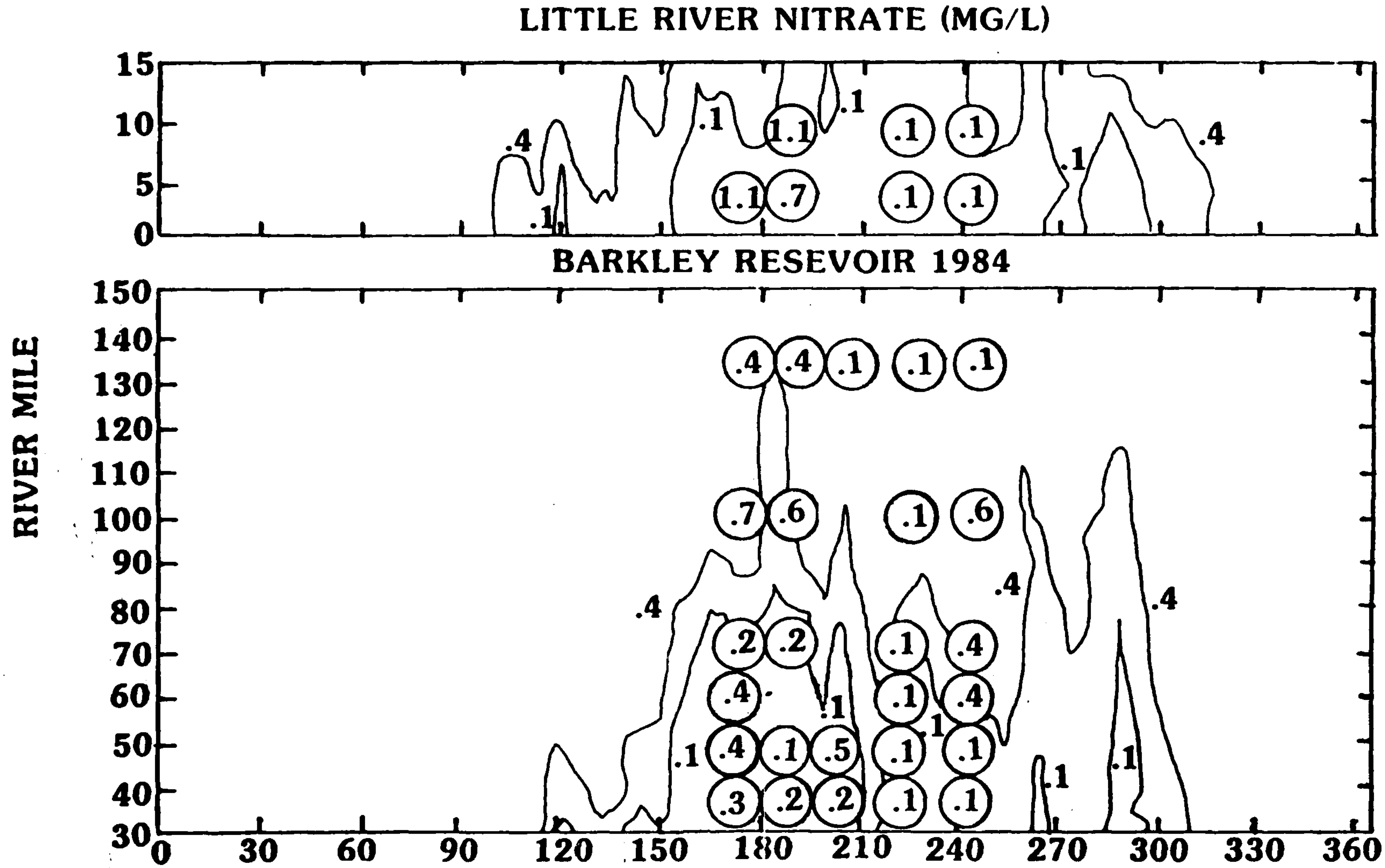
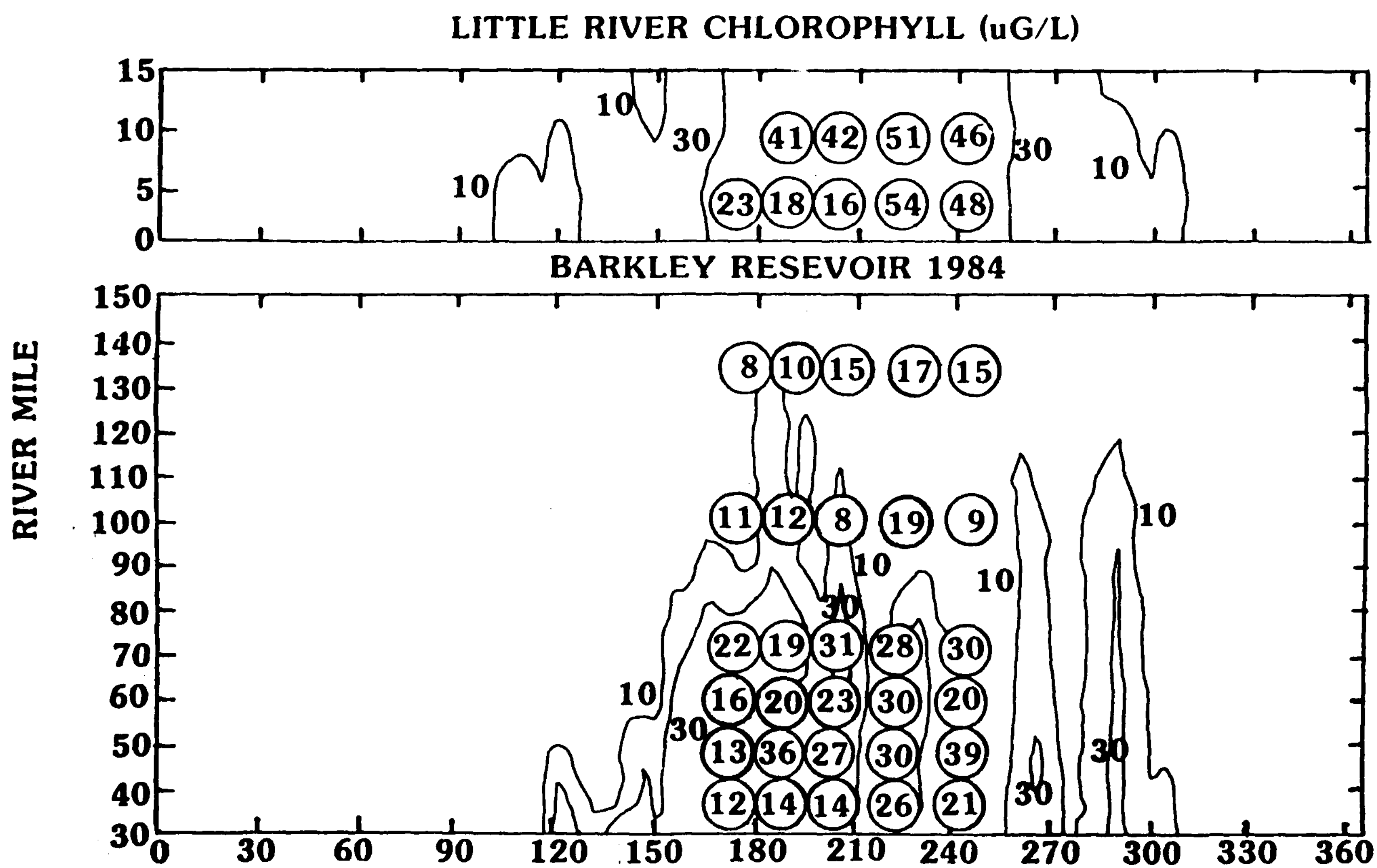


Figure 24 Modeled Surface Chlorophyll Patterns for 1984



were depleted, the chlorophyll declined in the downstream direction because of algal settling and respiration processes.

VALIDATION OF BRANCHED BETTER MODEL WITH OBSERVED BARKLEY DATA

Validation of the model was demonstrated by simulating 1985 and 1986 conditions without changing any model coefficients. These simulations generally matched the available data as well as the 1984 simulations. This increased the confidence in the accuracy of the model formulations, since both 1985 and 1986 were much lower flow years with correspondingly greater observed changes in water quality resulting from the stronger stratification events and longer residence times. Examining the simulations from all three years together with the observed data reveals several characteristics of Lake Barkley water quality which should be useful for management purposes in the future.

Available Lake Water Quality Data During 1985 and 1986

Field data were collected at approximately two week intervals from May to October of 1985 from four main channel and eleven embayment stations. Monthly data were obtained from November of 1985 through August of 1986, although the number of stations sampled varied each month. The surface and bottom data for the model variables were arranged into files for plotting with the model predictions, as was done for the 1984 calibration task. The 1985 field surveys were the most extensive of the three years, with eleven sampling trips, and provided a good test for the model simulations. The 1986 data were quite limited, although the flows were lower and the model predicted more extreme stratification and DO depletion. Overall, the available field data were

exceptional and provided an opportunity to examine the general validity of the model formulations for two years, in addition to the 1984 calibration year.

Temperature Validations

The stratification patterns during 1985 and 1986 were more stable and persistent than during 1984, although intermittent mixing did occur following cooling events. Stratification was generally stronger in 1986, since the flows were lower. With the exception of a few cool data values, the available data confirmed the modeled temperature patterns. Both surface and bottom temperatures were close to observed values. Since the data were measured at bi-weekly or monthly intervals, the model predicts many intervening heating and cooling events which caused mixing or increased stratification. These short term dynamics cannot be validated with the periodic data, but the general seasonal stratification patterns were well reproduced with the model. The simulated temperature patterns and observed surface and bottom data at the four key stations during 1985 are shown in Figures 25 to 28. Plots for 1986 are shown in Figures 36 to 39.

The surface temperature patterns for these two validation years are shown in Figures 29 and 40. Surface temperatures were quite warm during 1986, reaching a maximum of 35° C in July. The effects of the Cumberland Steam Plant was not dominant, since the surface temperatures were already near equilibrium, so that mixing and heat exchange downstream of the thermal discharge reduced the temperature rise caused by the thermal effluent.

Residence Time Patterns

The modeled residence time patterns for 1985 and 1986 are shown in Figures 30 and 41. In comparison to the residence times of 1984, both validation years

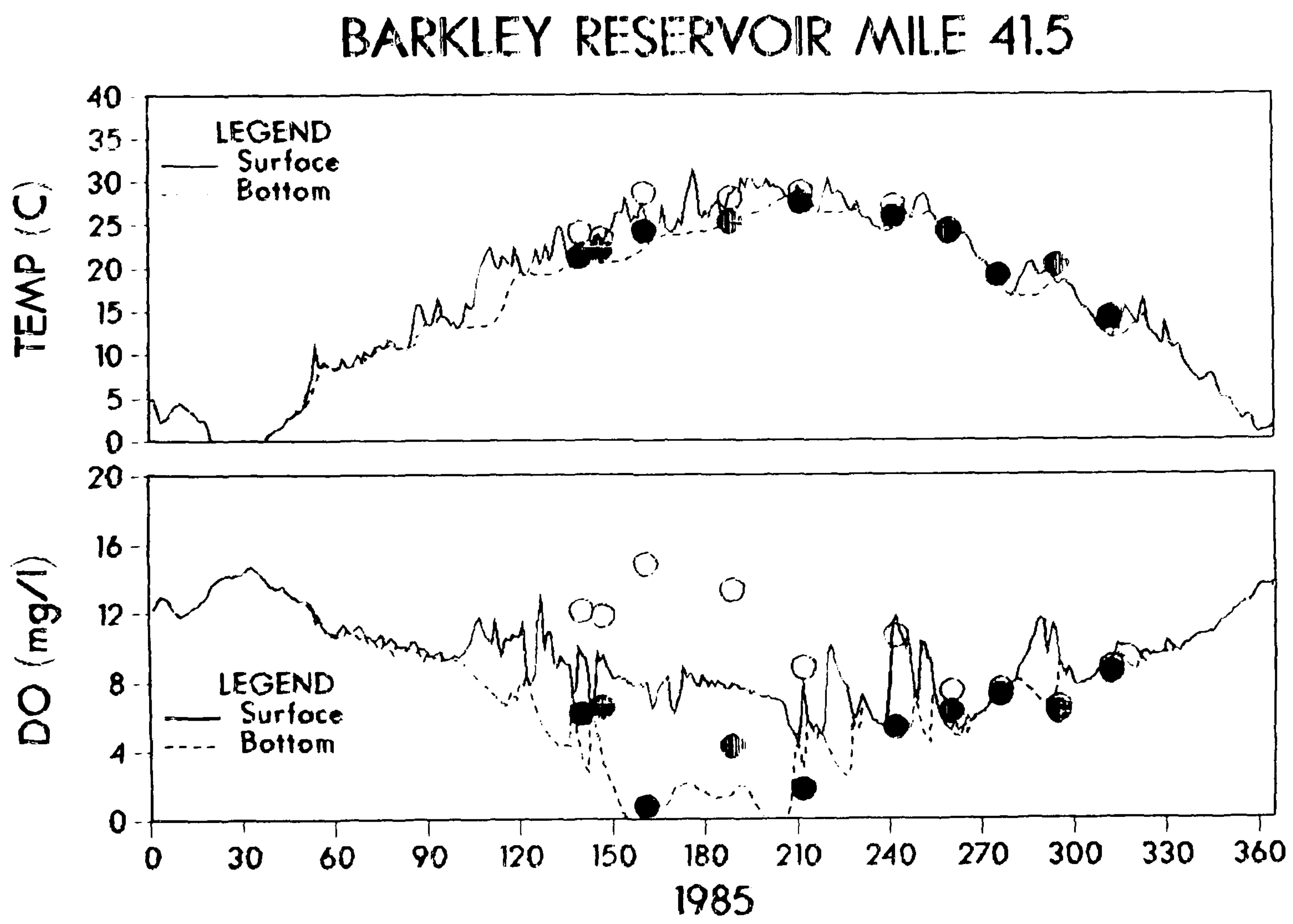


Figure 25 Validation Results at CuRM 41.5 for 1985

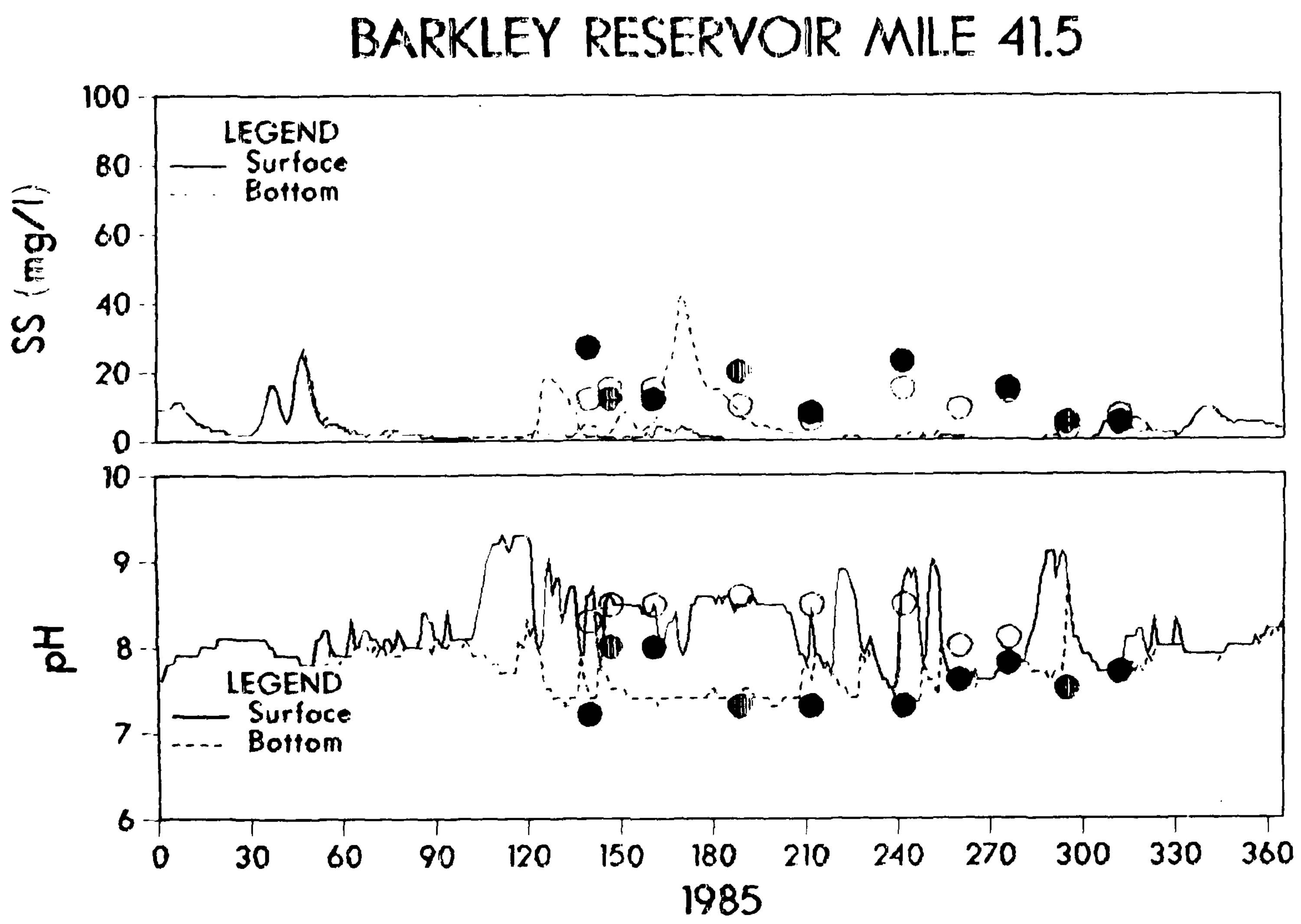
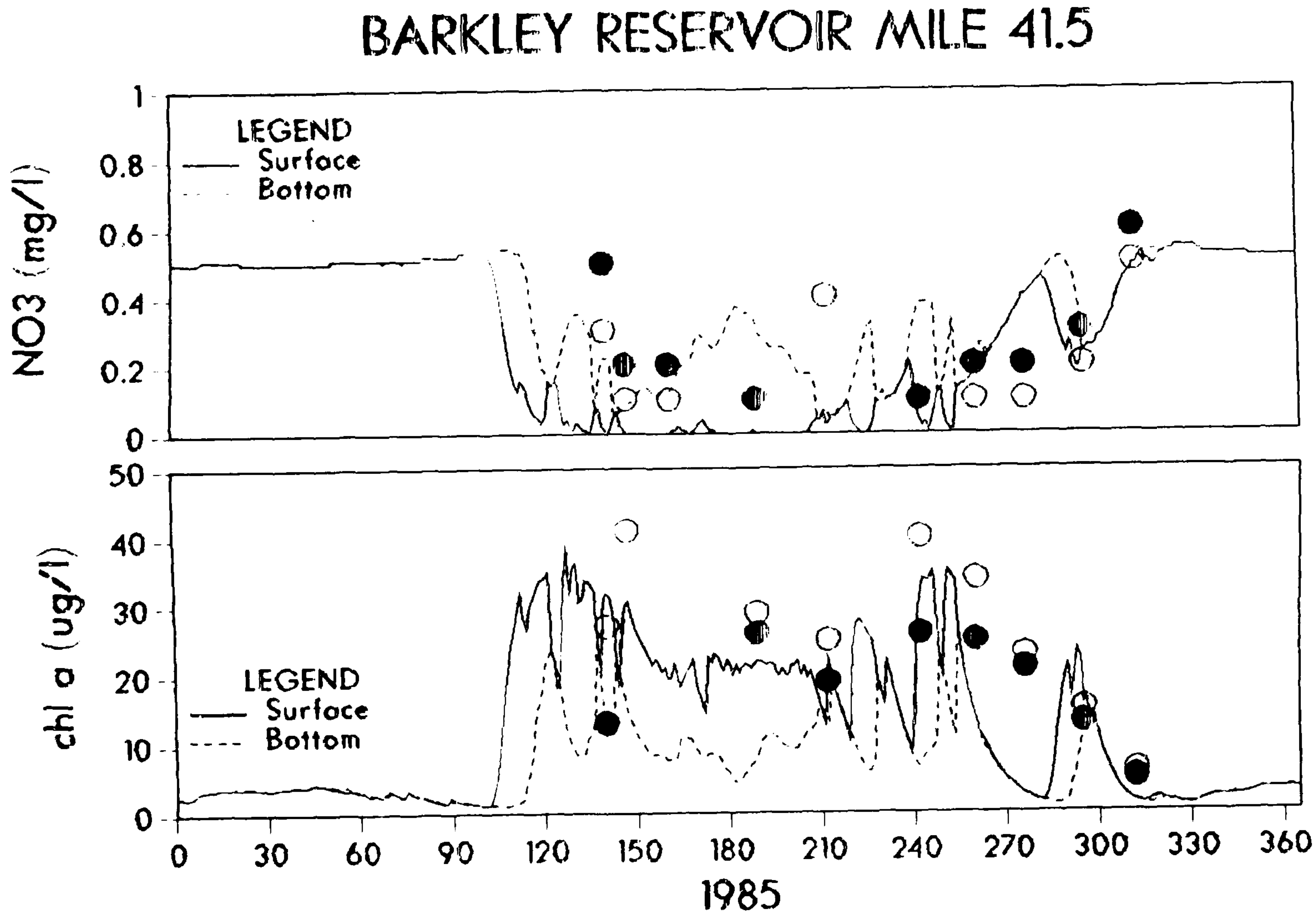


Figure 25 (continued)



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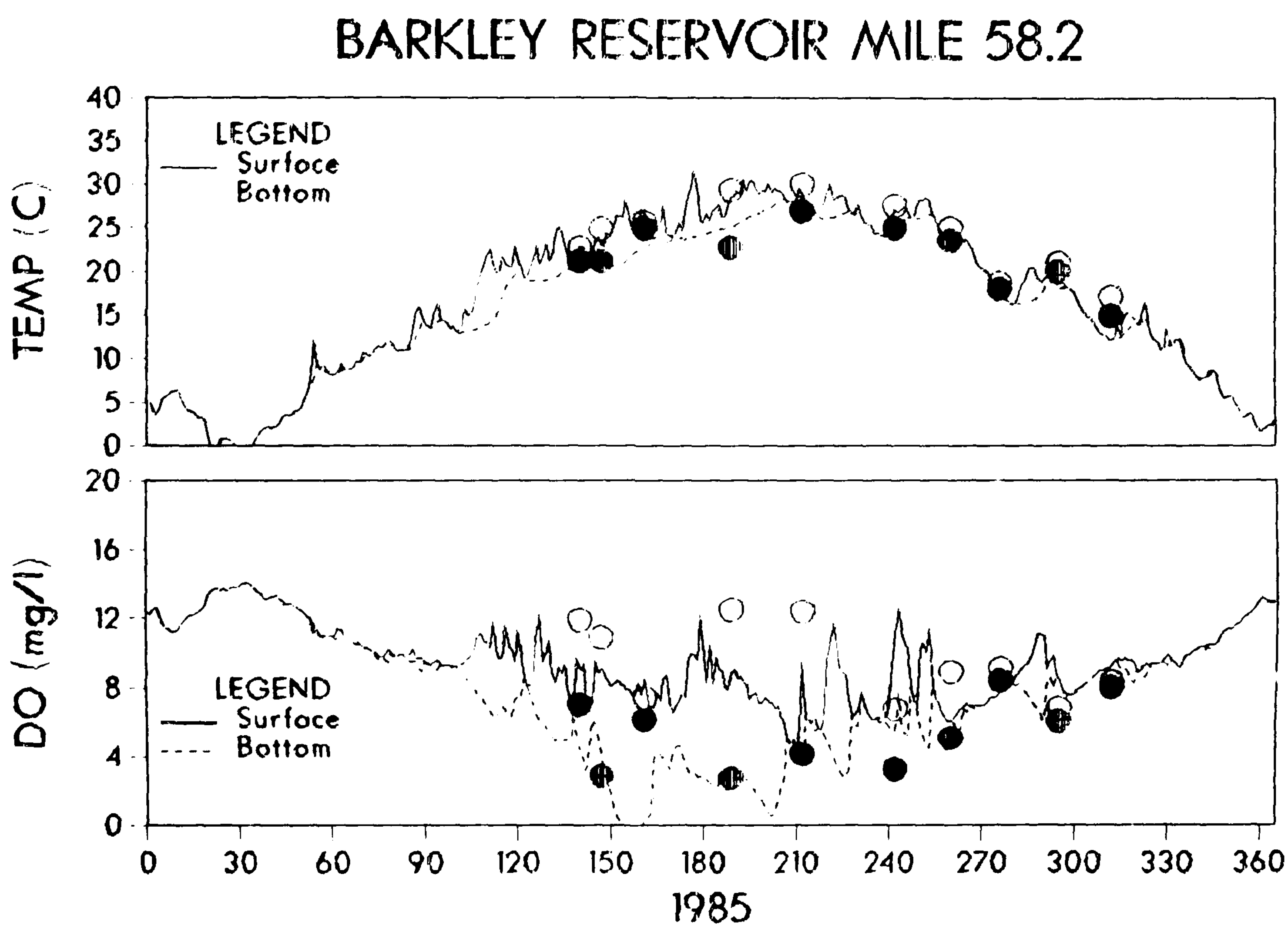
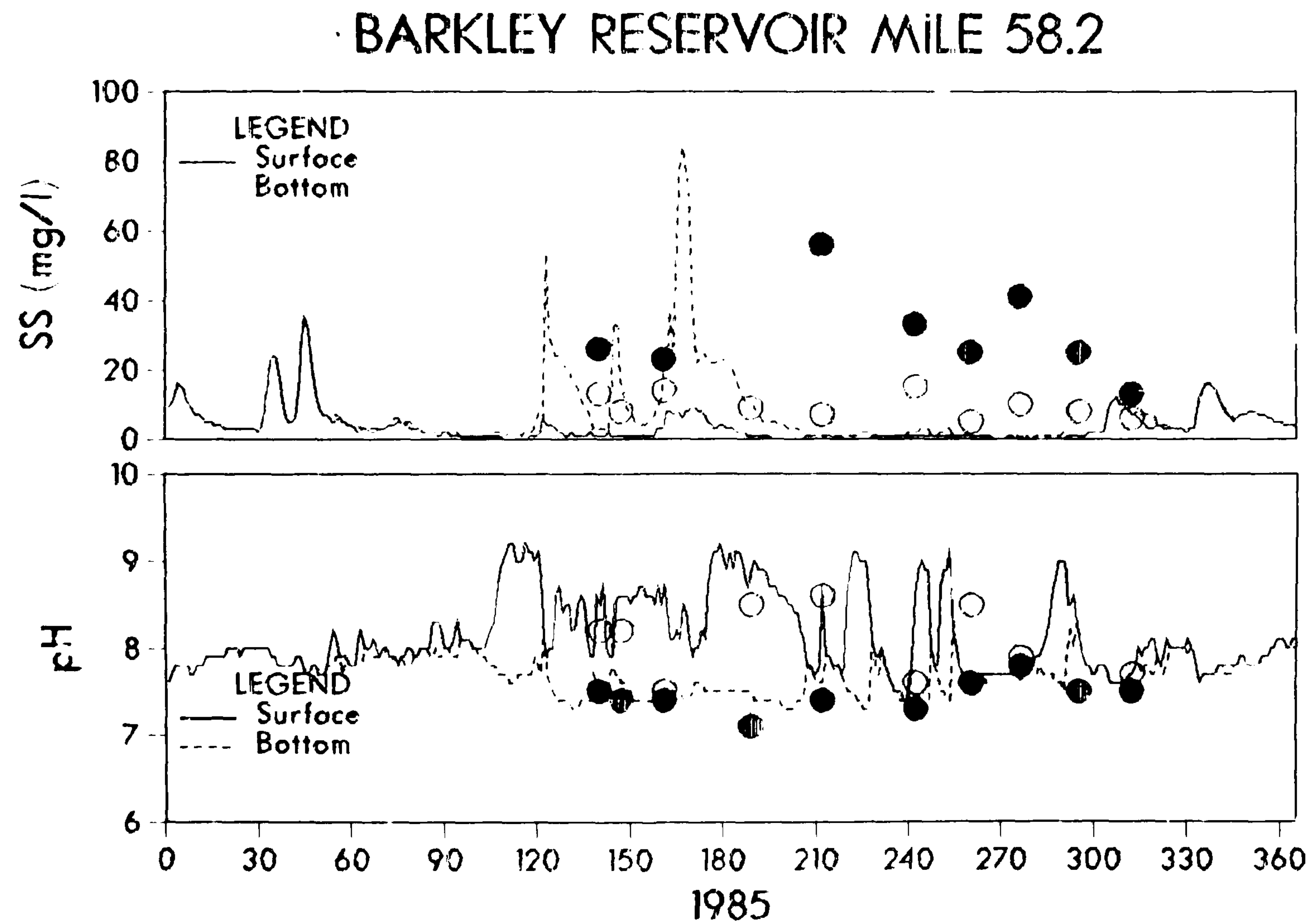


Figure 26 Validation Results at CuRM 58.2 for 1985



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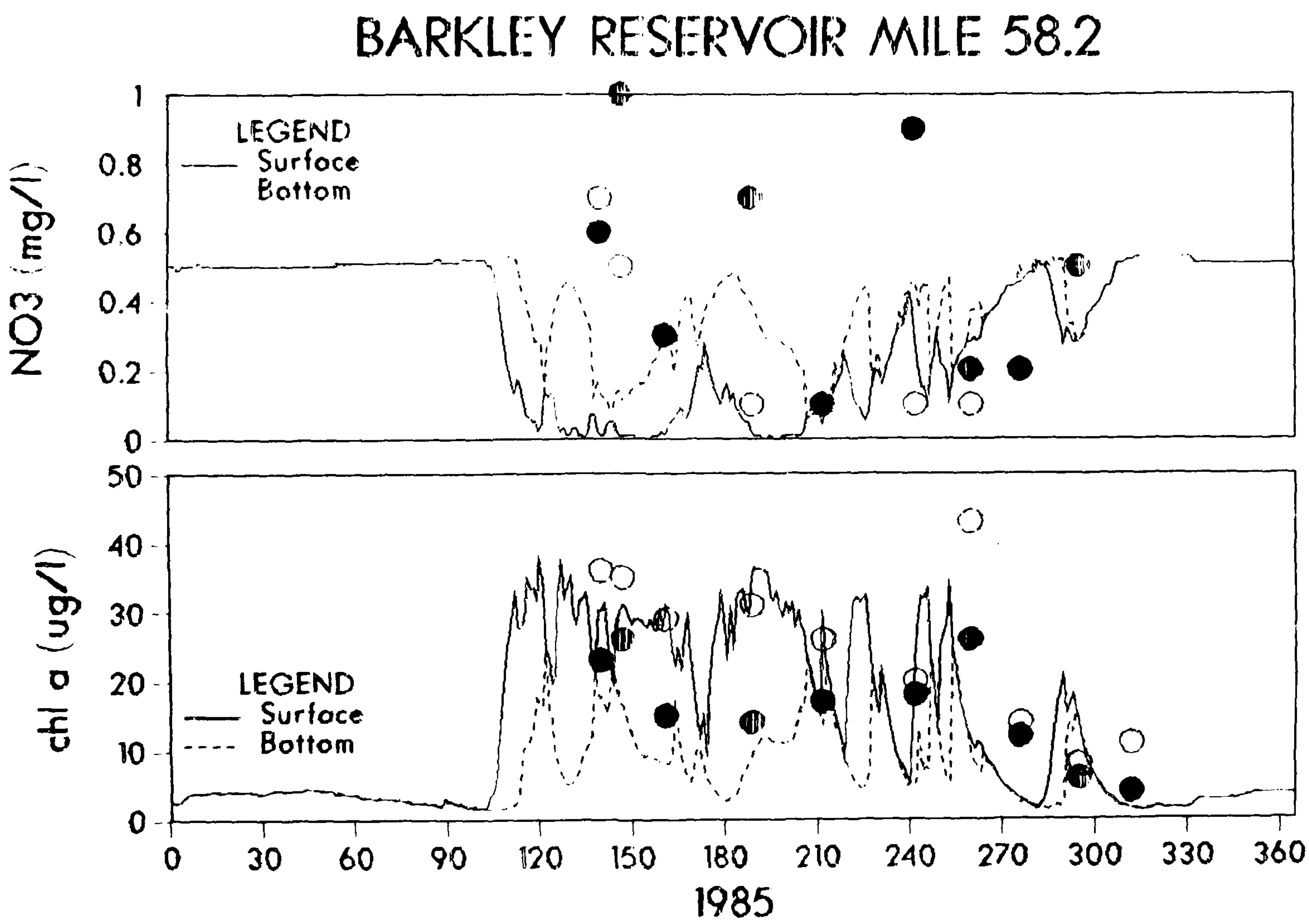

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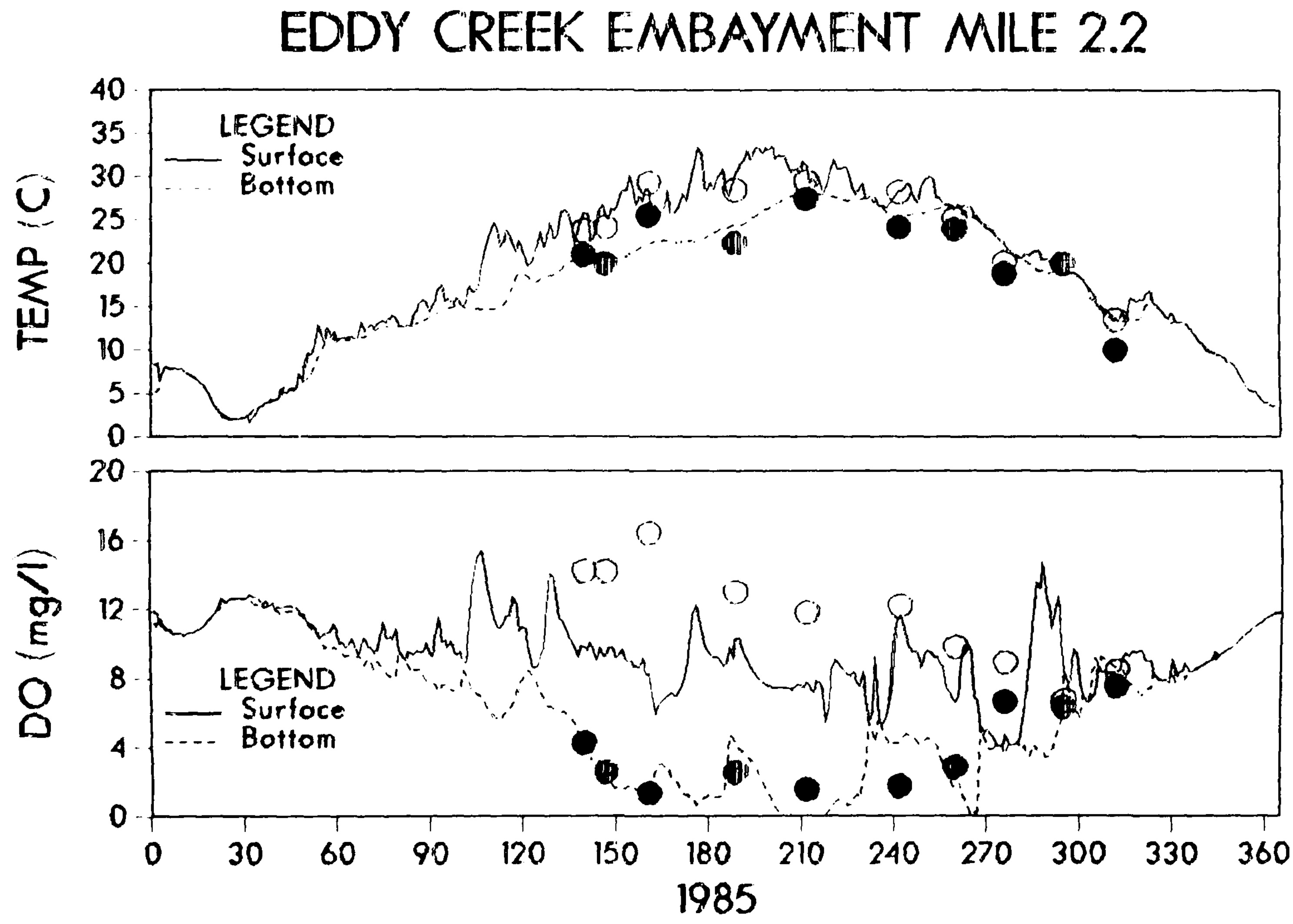
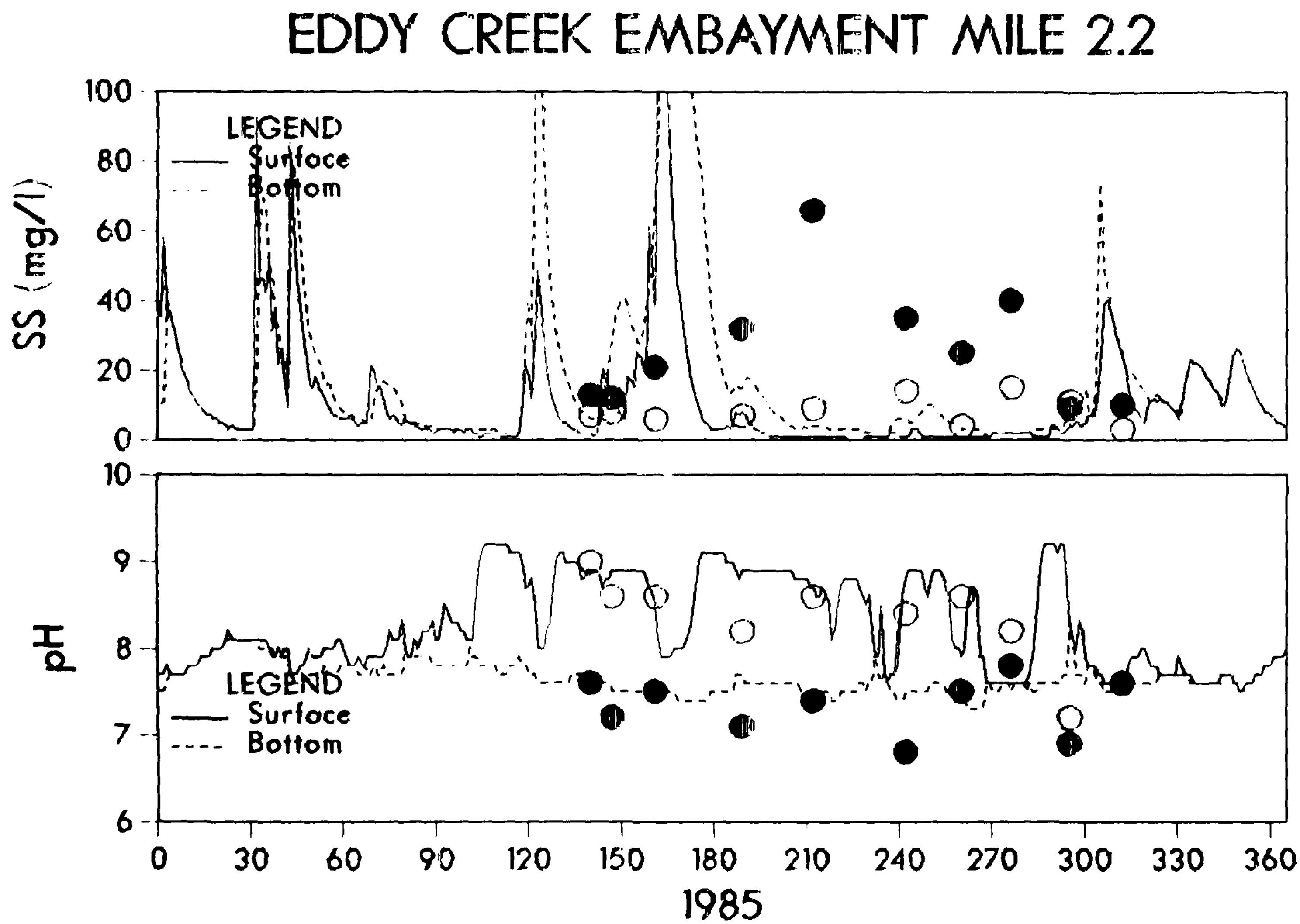


Figure 27 Validation Results at Eddy Creek Mile 2.2 for 1985



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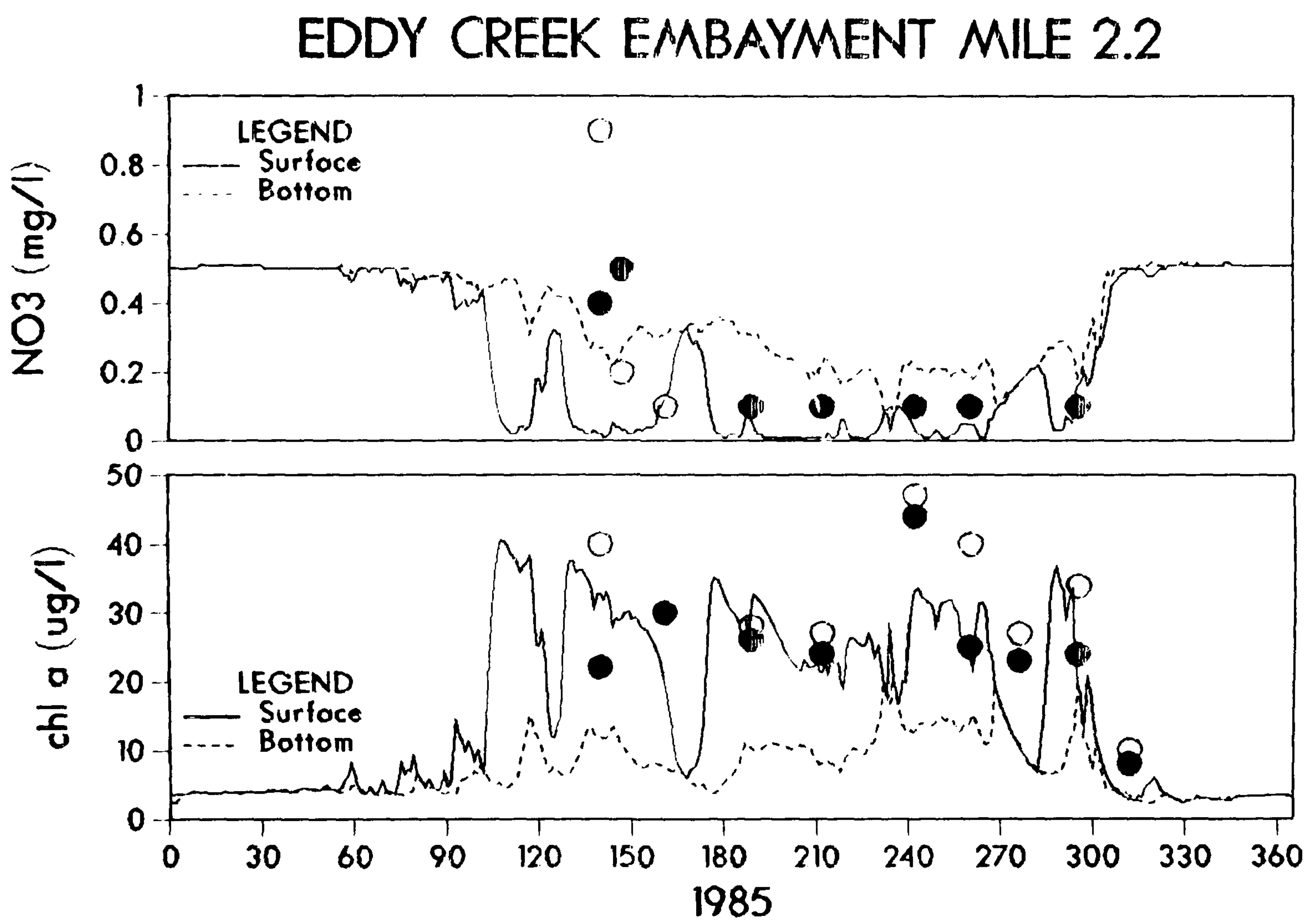

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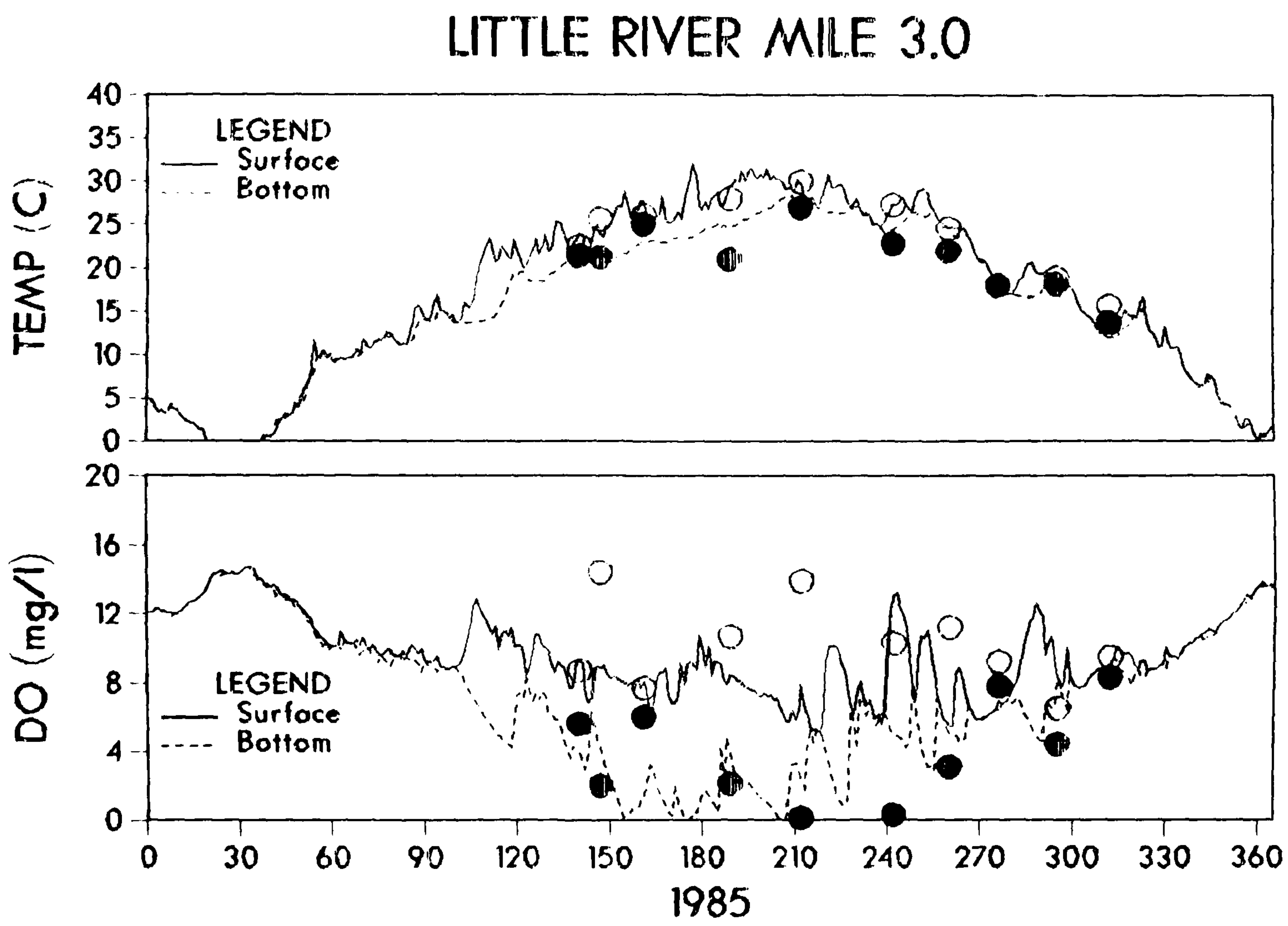
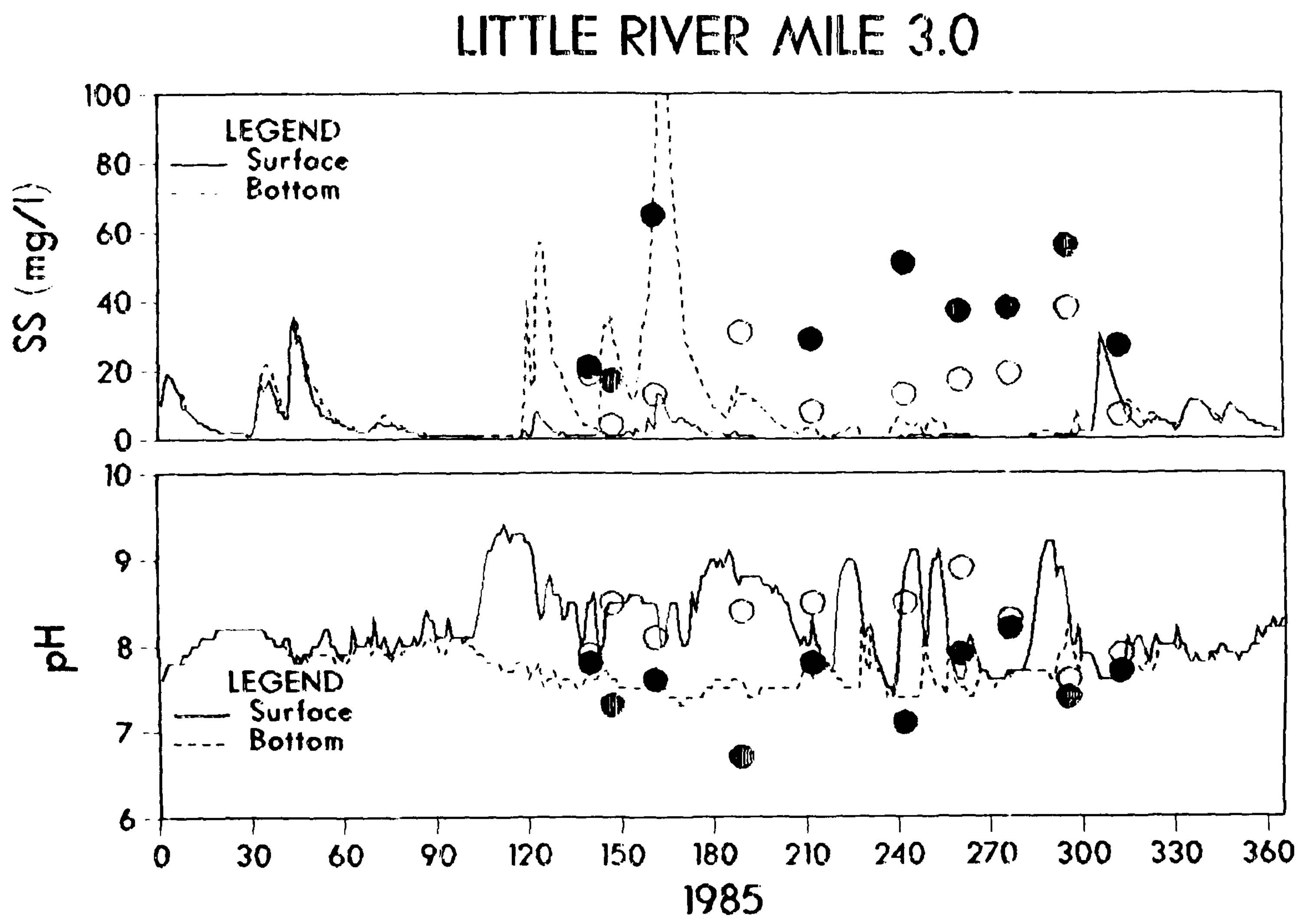


Figure 28 Validation Results at Little River Mile 3.0 for 1985



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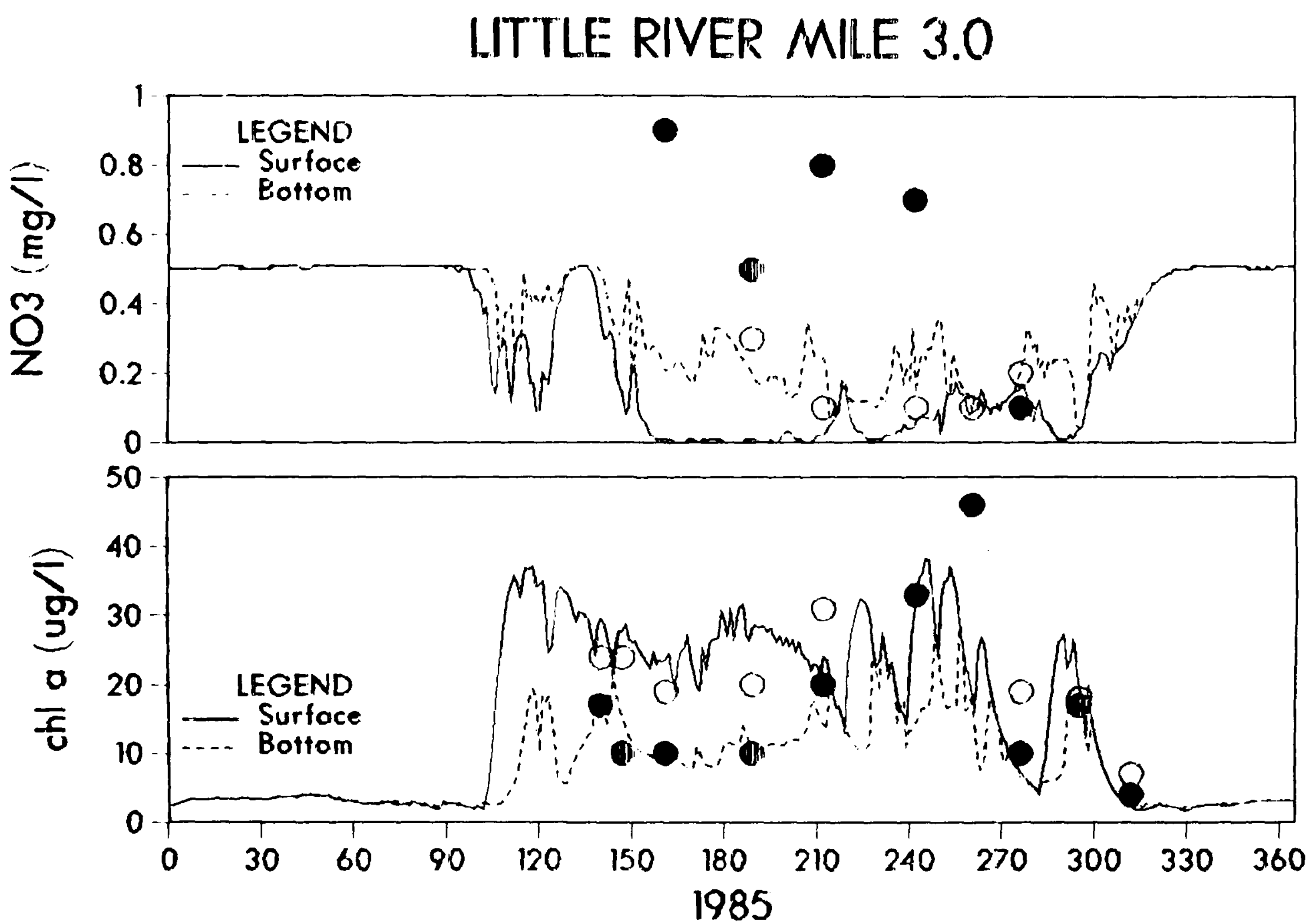


Figure 28 (continued)

Figure 29 Modeled Surface Temperature Patterns for 1985

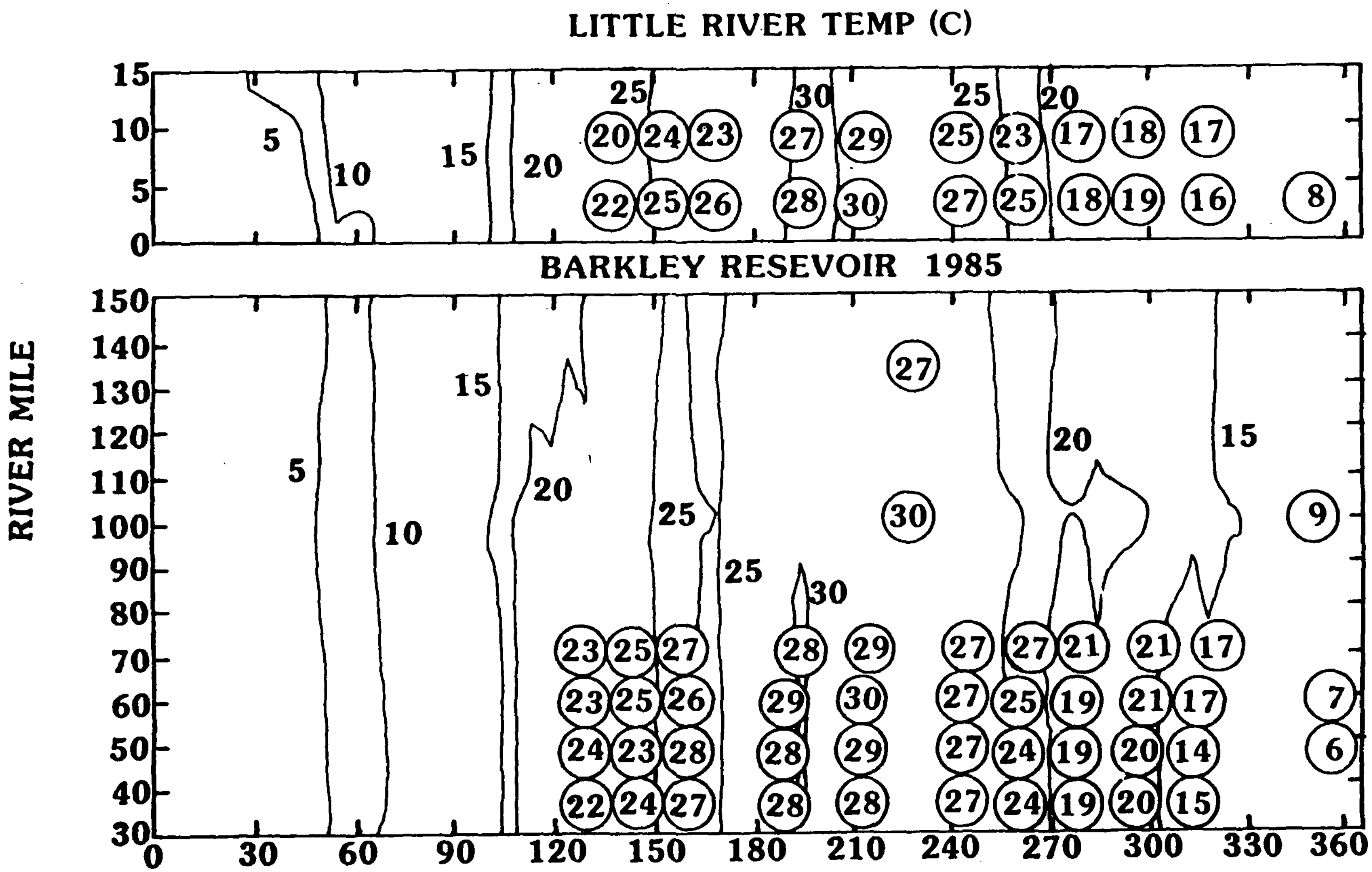


Figure 30 Modeled Surface Residence Time Patterns for 1985

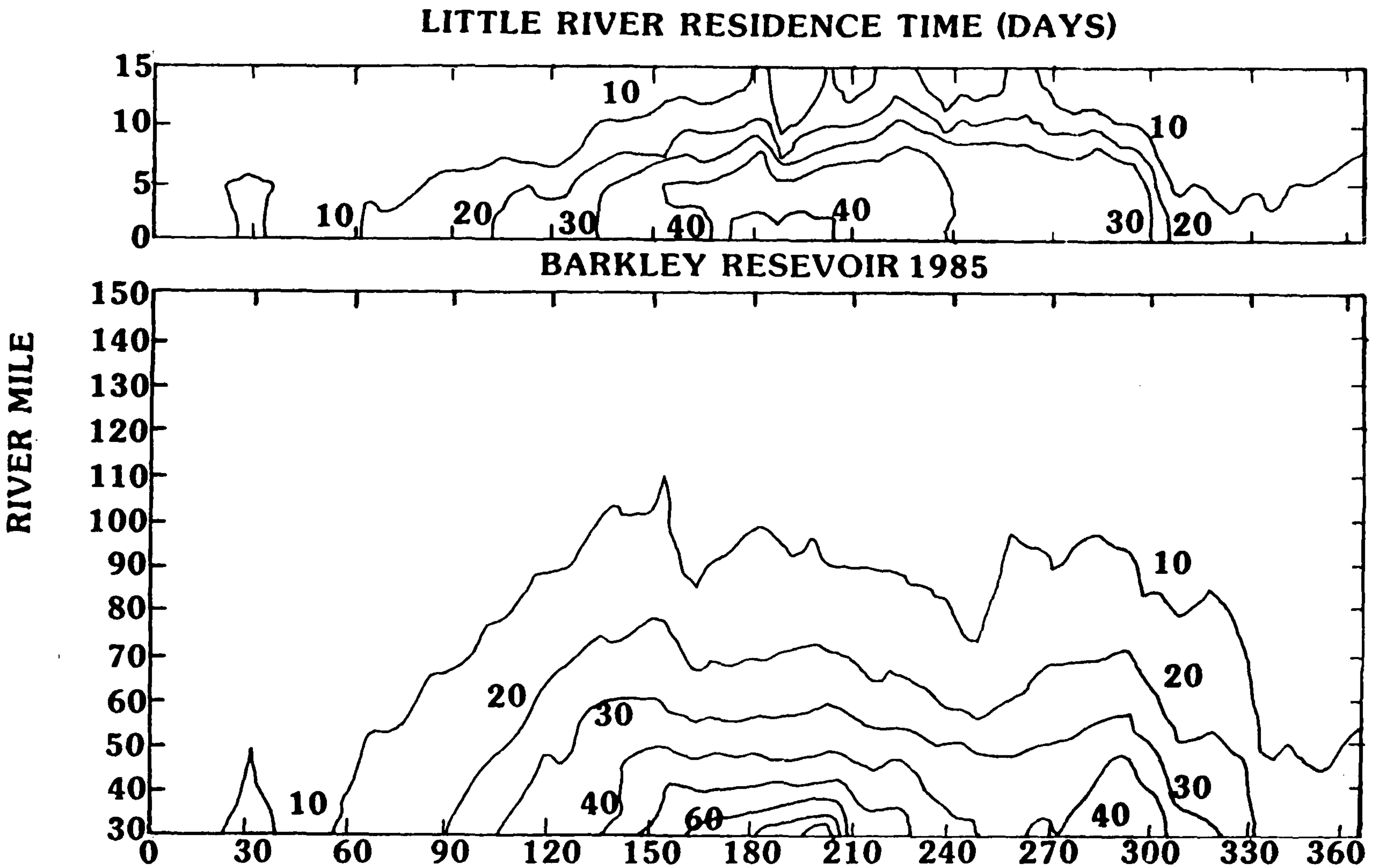


Figure 31 Modeled Surface DO Patterns for 1985

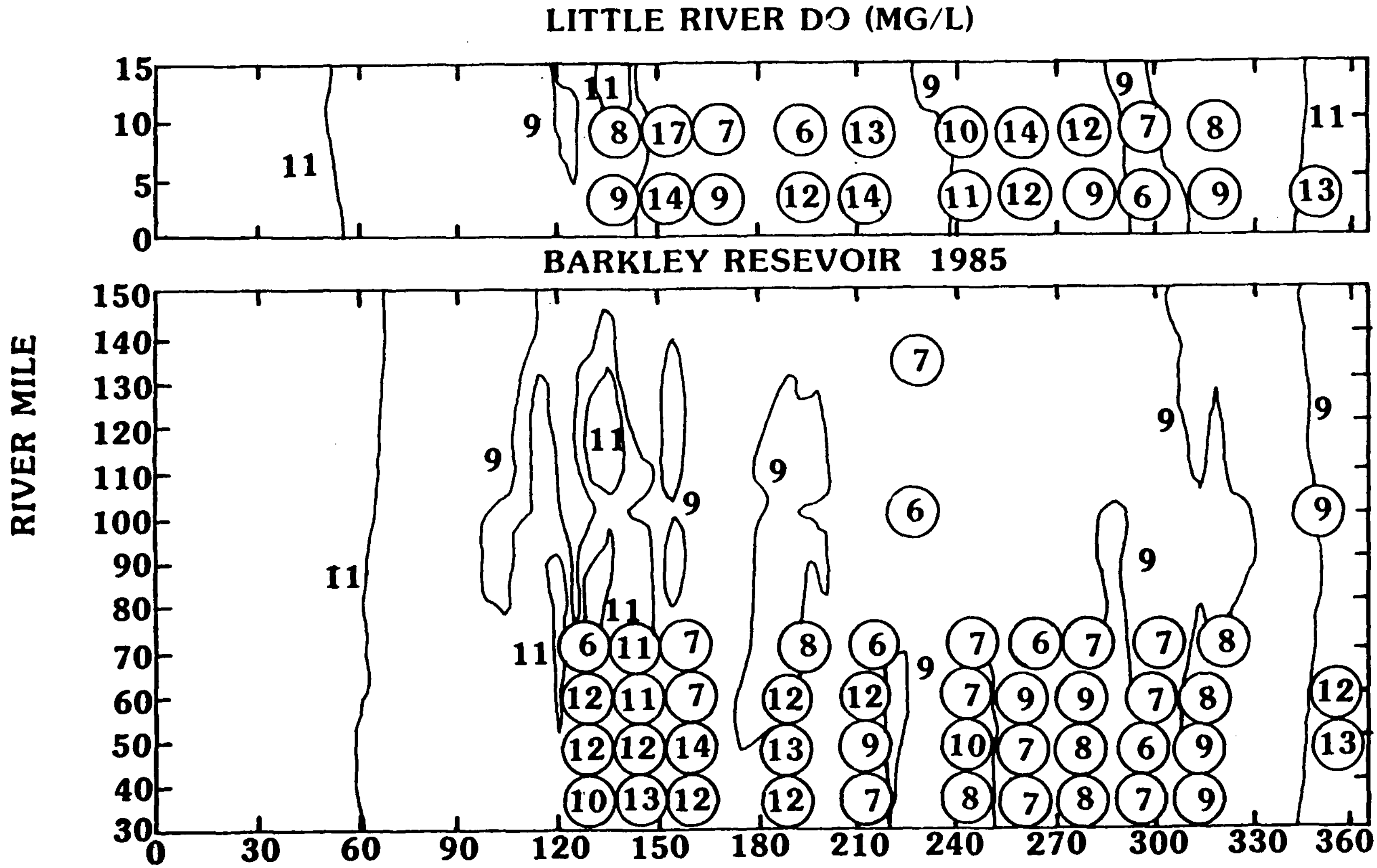


Figure 32 Modeled Surface SS Patterns for 1985

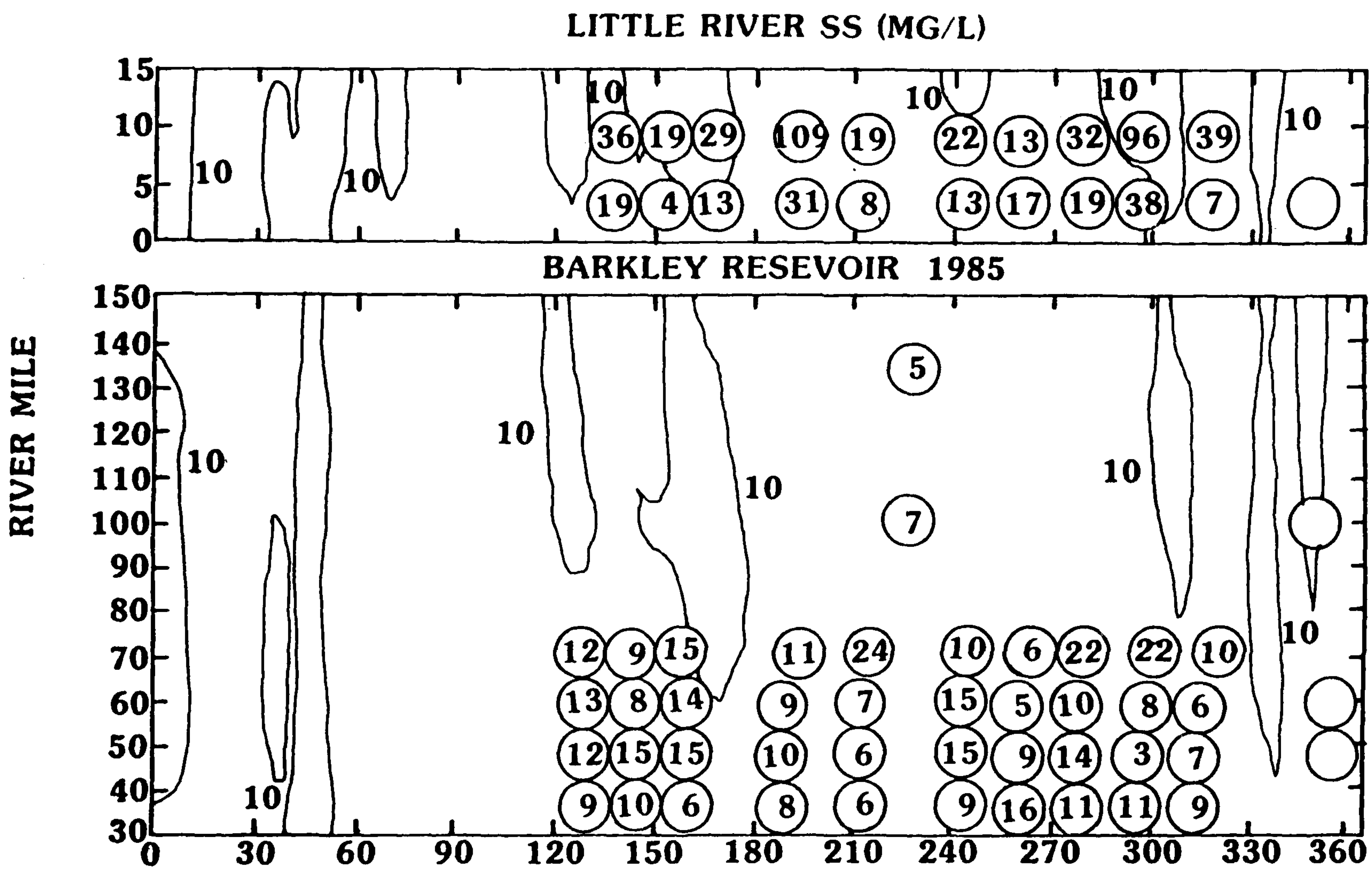


Figure 33 Modeled Surface pH Patterns for 1985

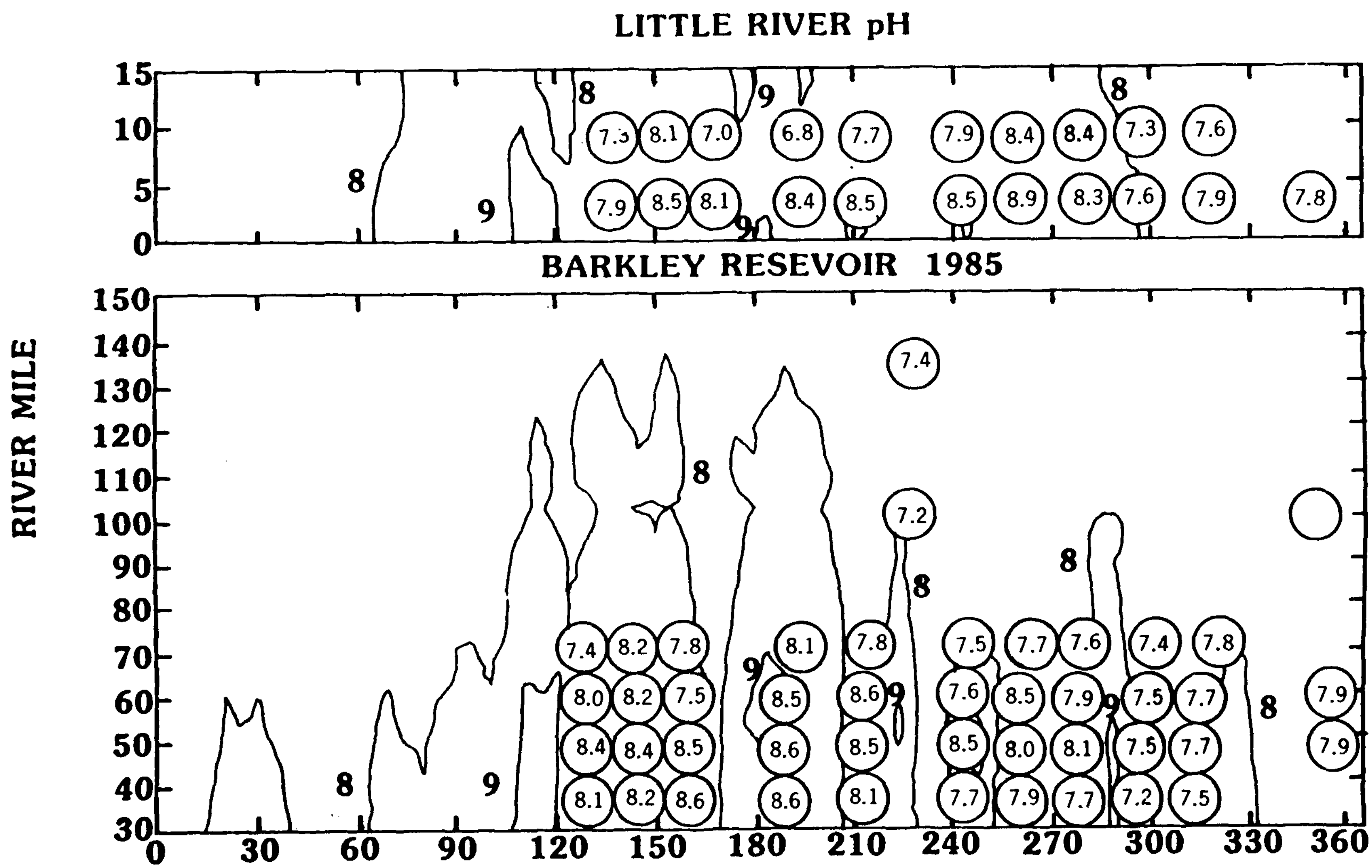


Figure 34   Modeled Surface Nitrate Patterns for 1985

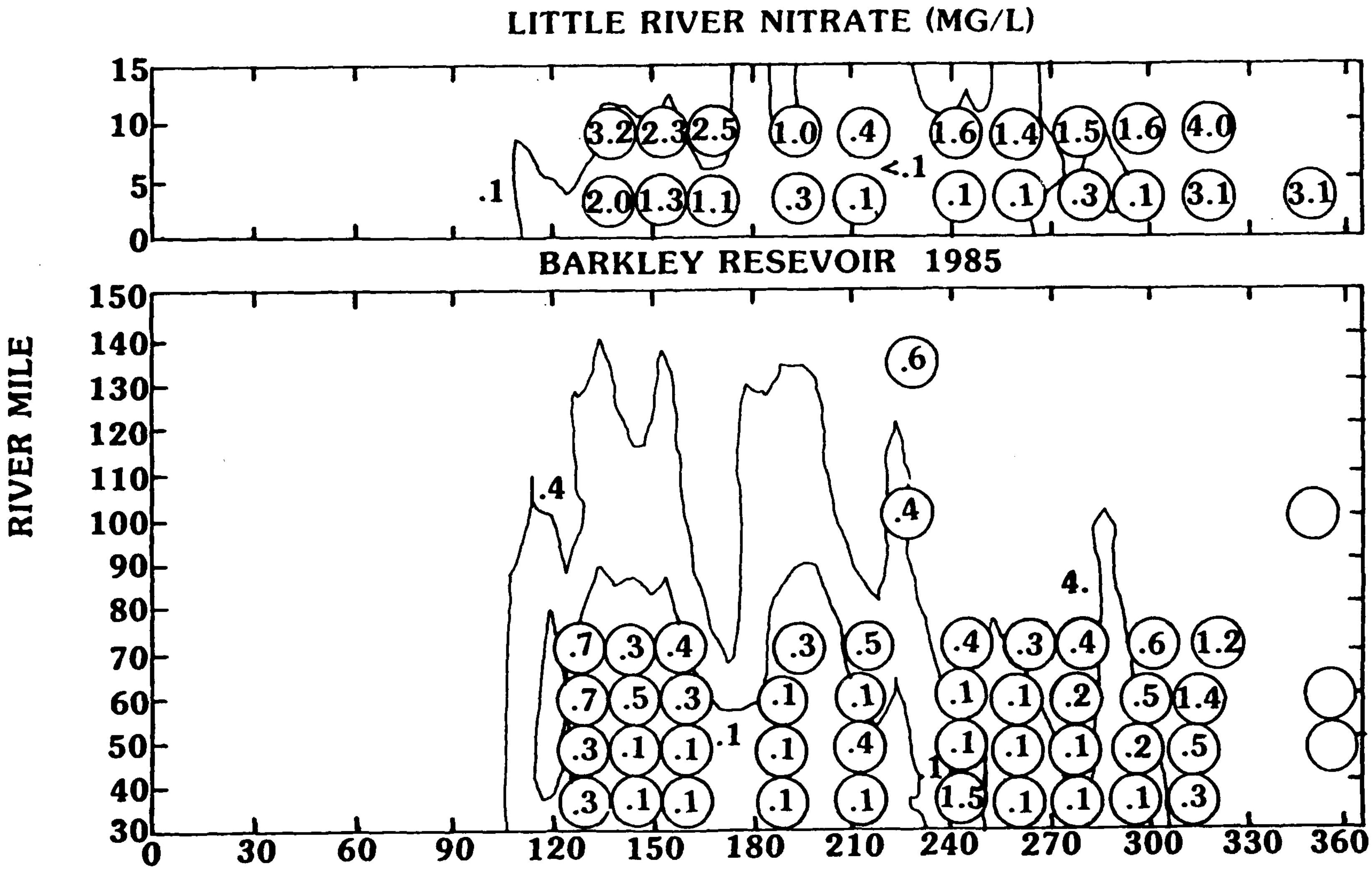
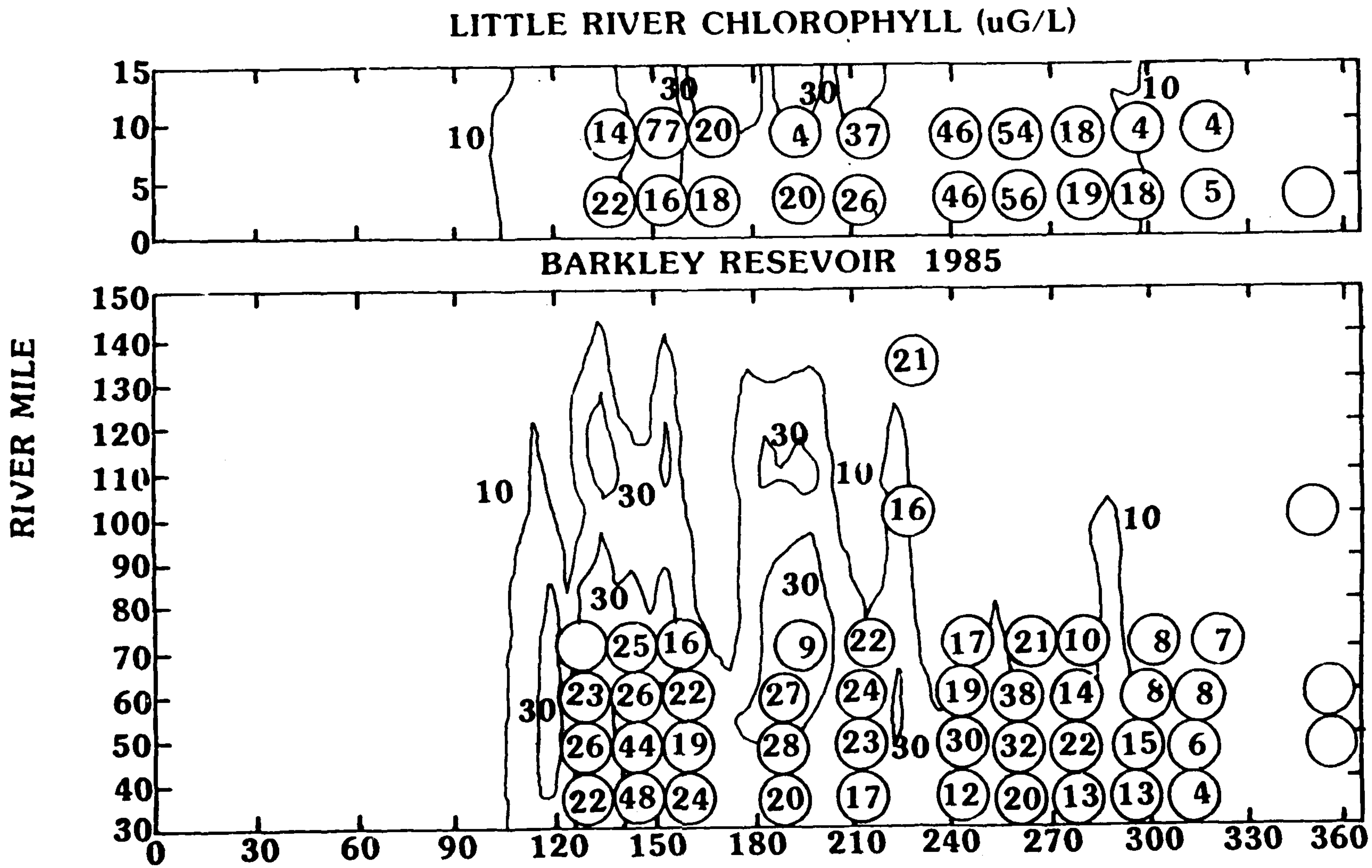


Figure 35 Modeled Surface Chlorophyll Patterns for 1985



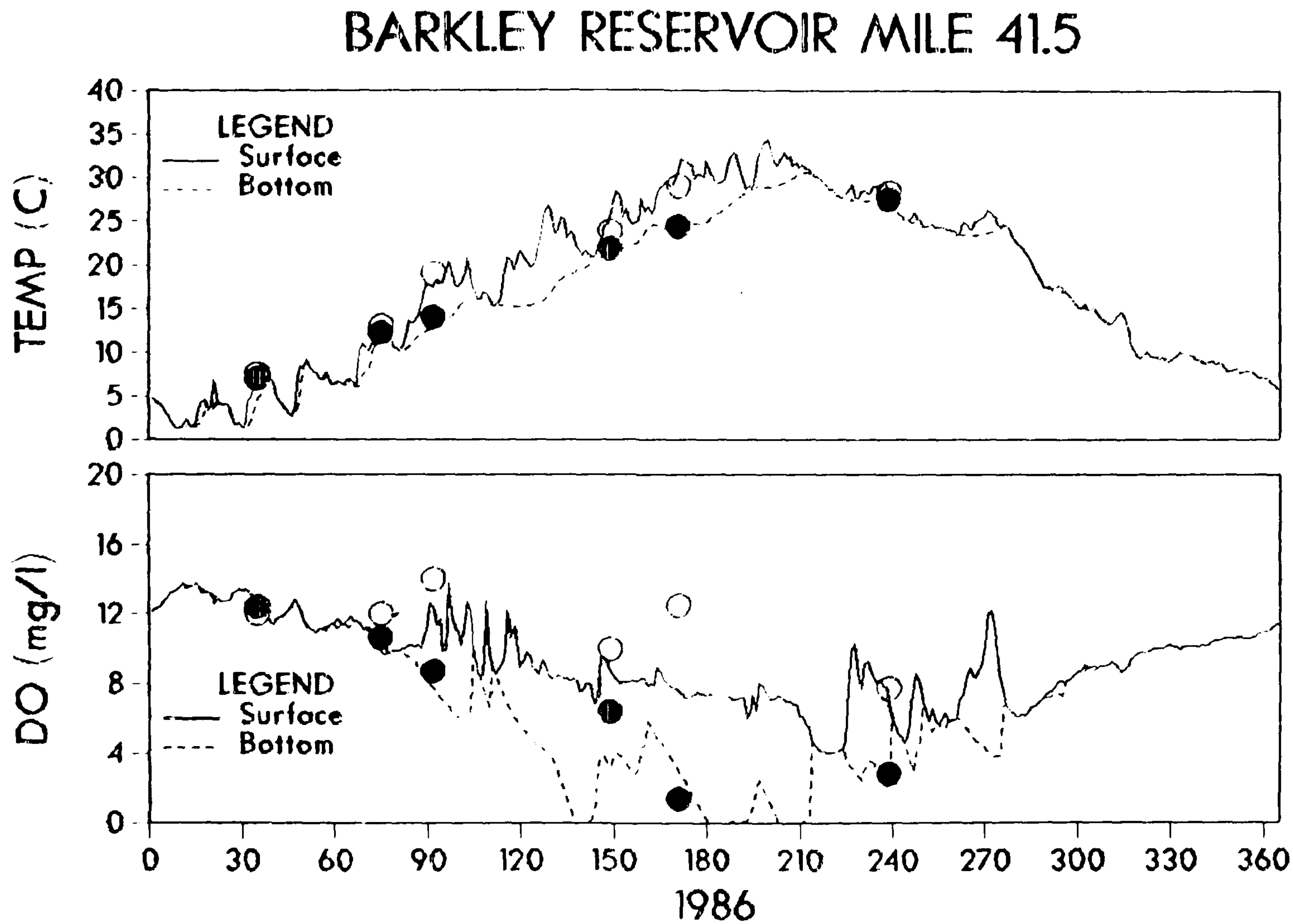


Figure 36 Validation Results at CuRM 41.5 for 1986

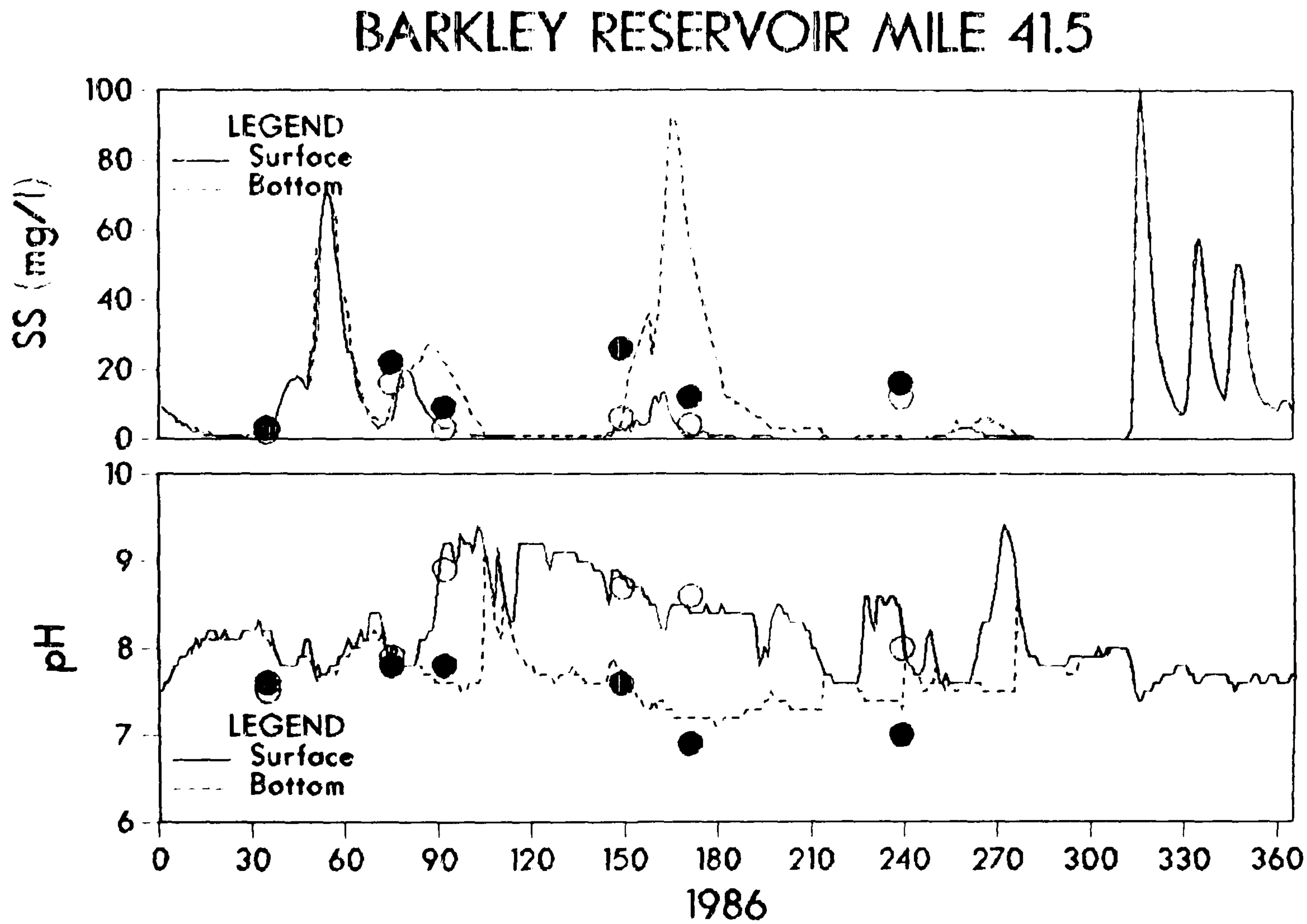
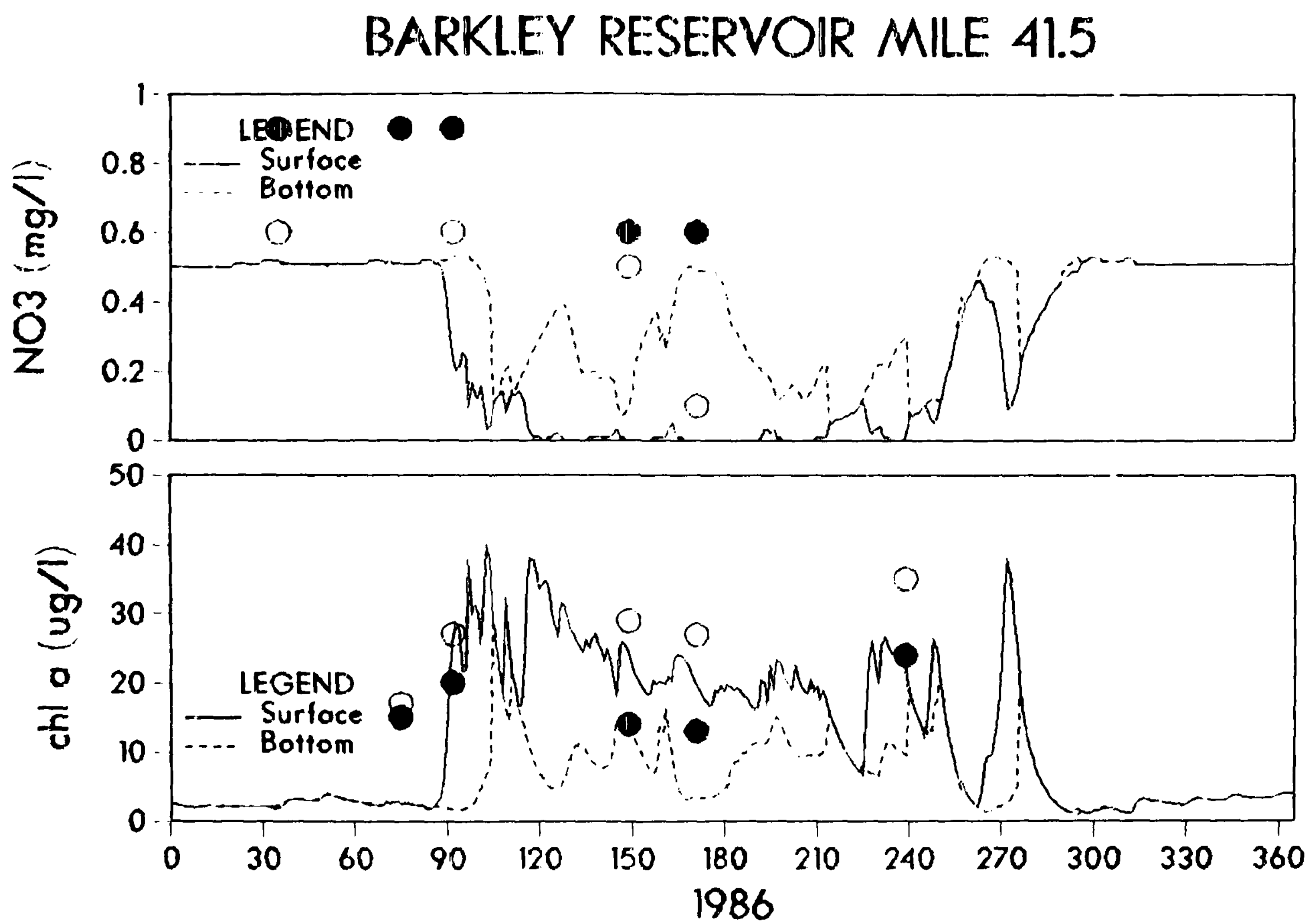


Figure 36 (continued)



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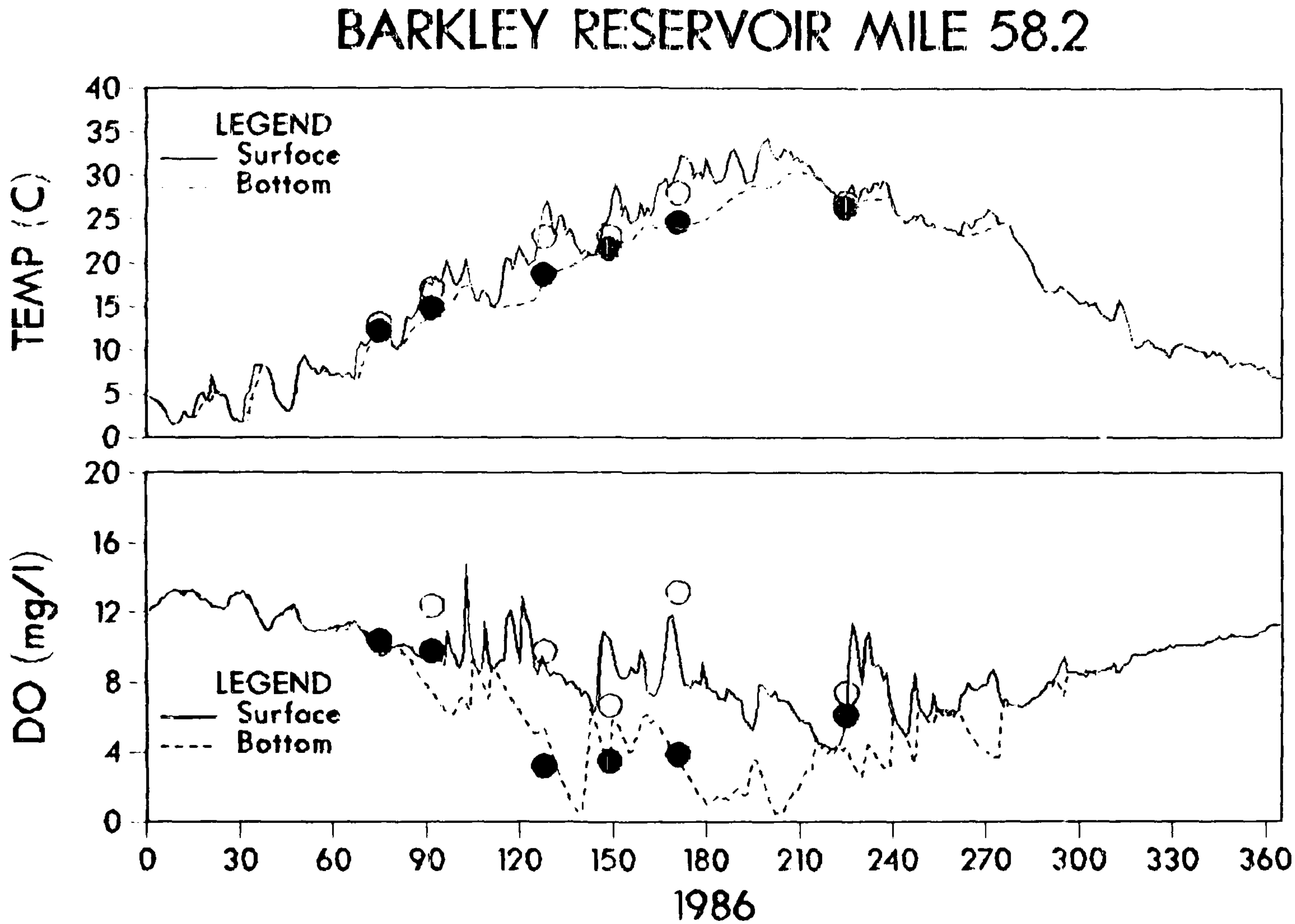
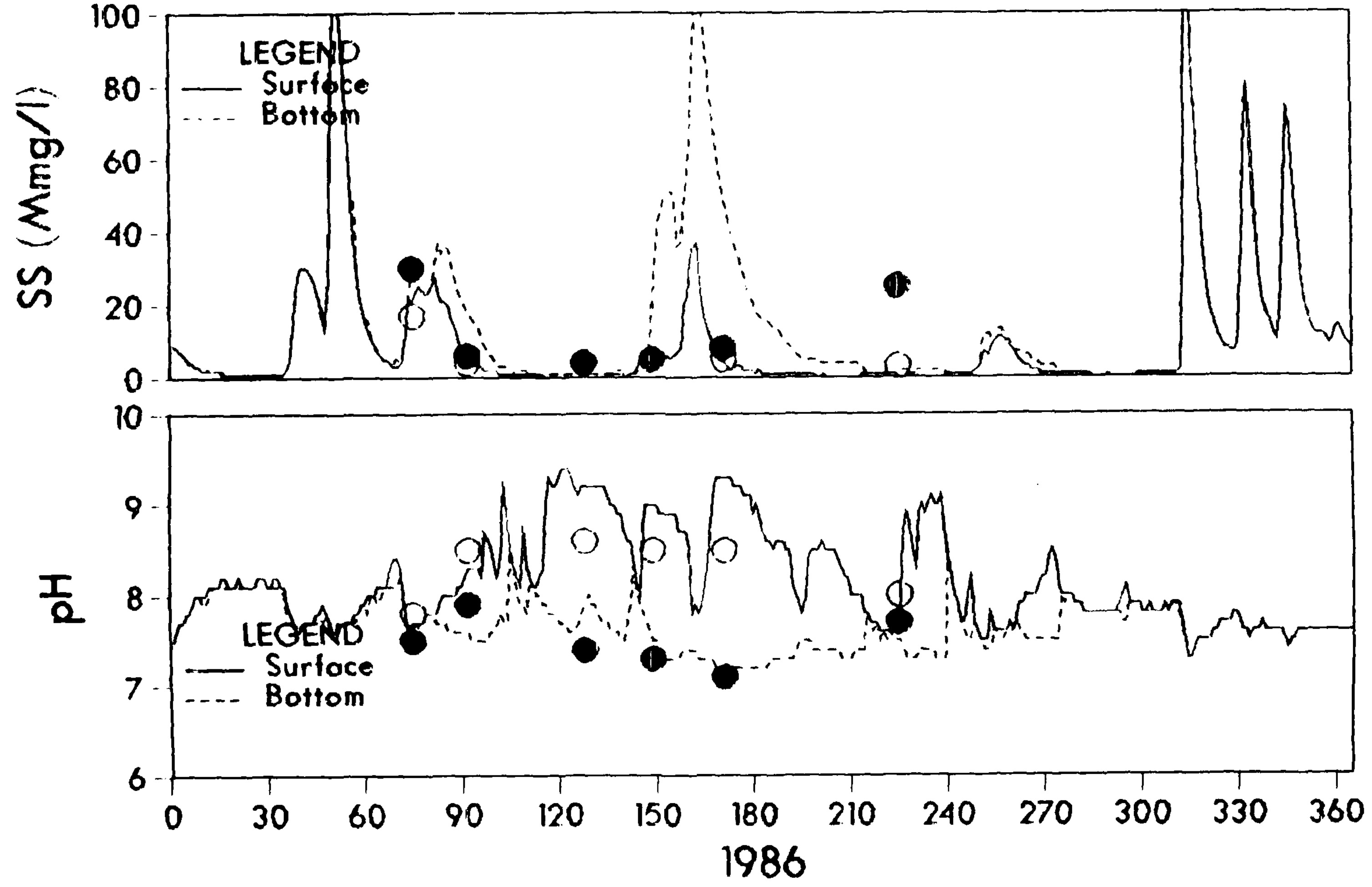


Figure 37 Validation Results at CuRM 58.2 for 1986

BARKLEY RESERVOIR MILE 58.2



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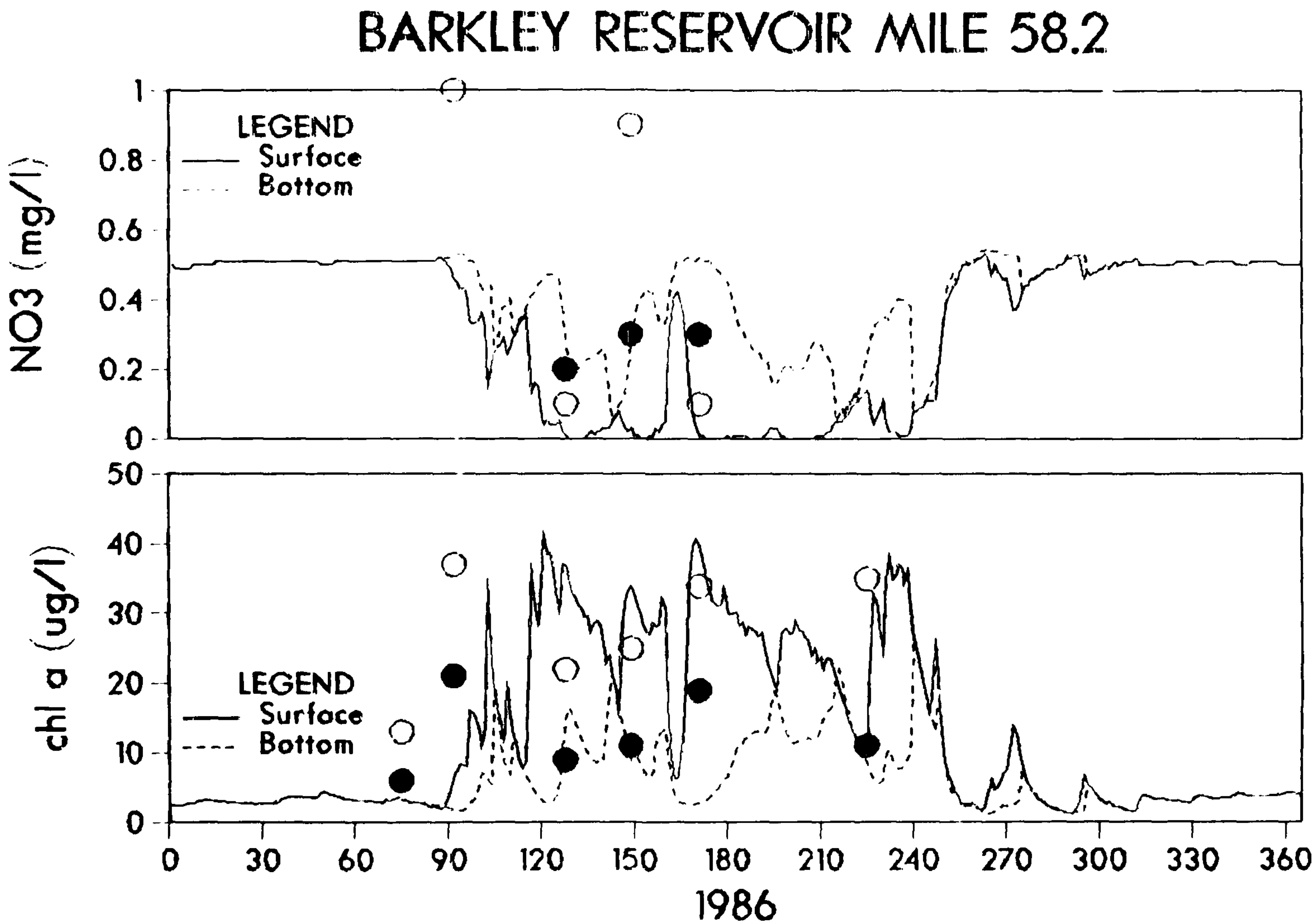

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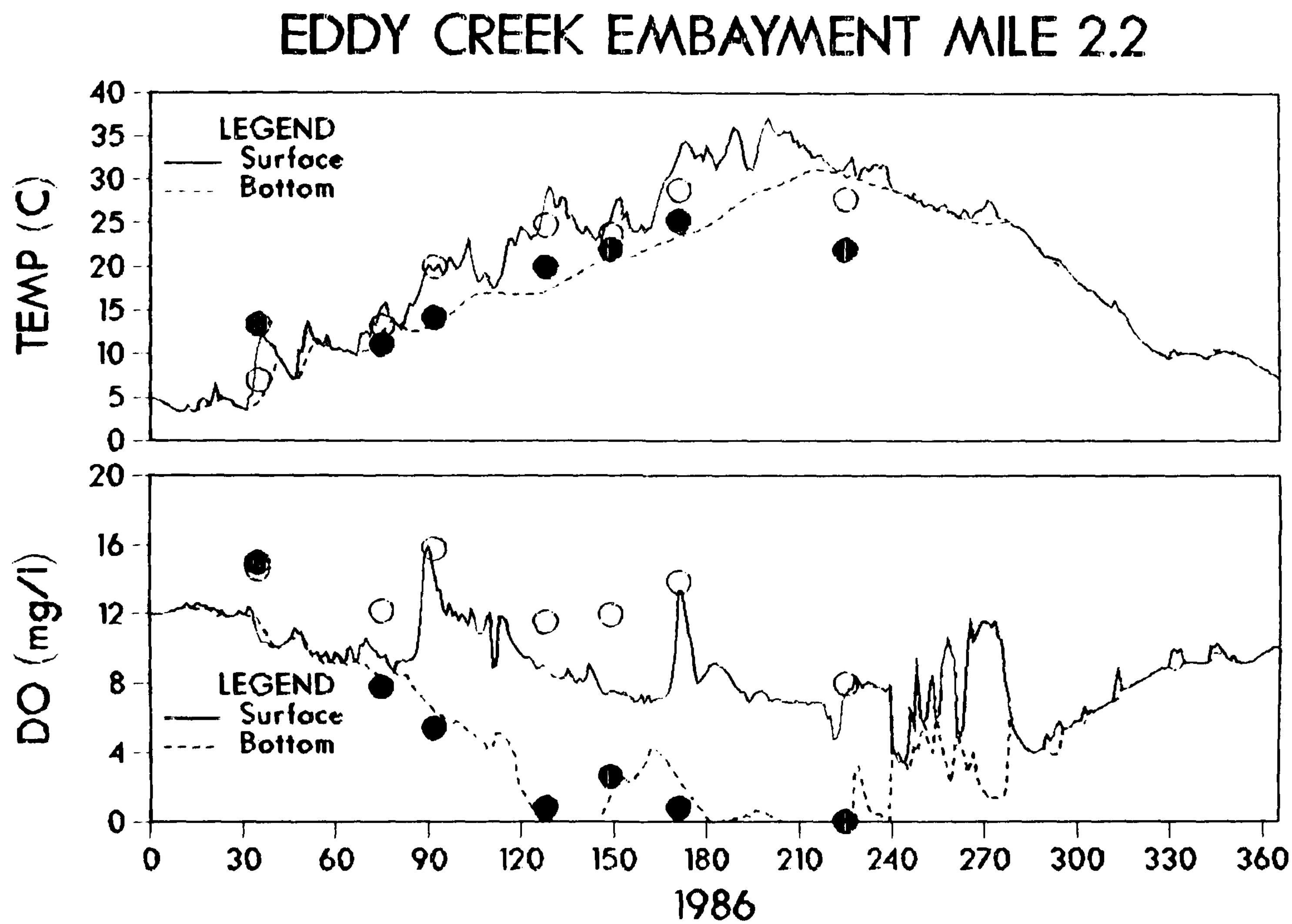
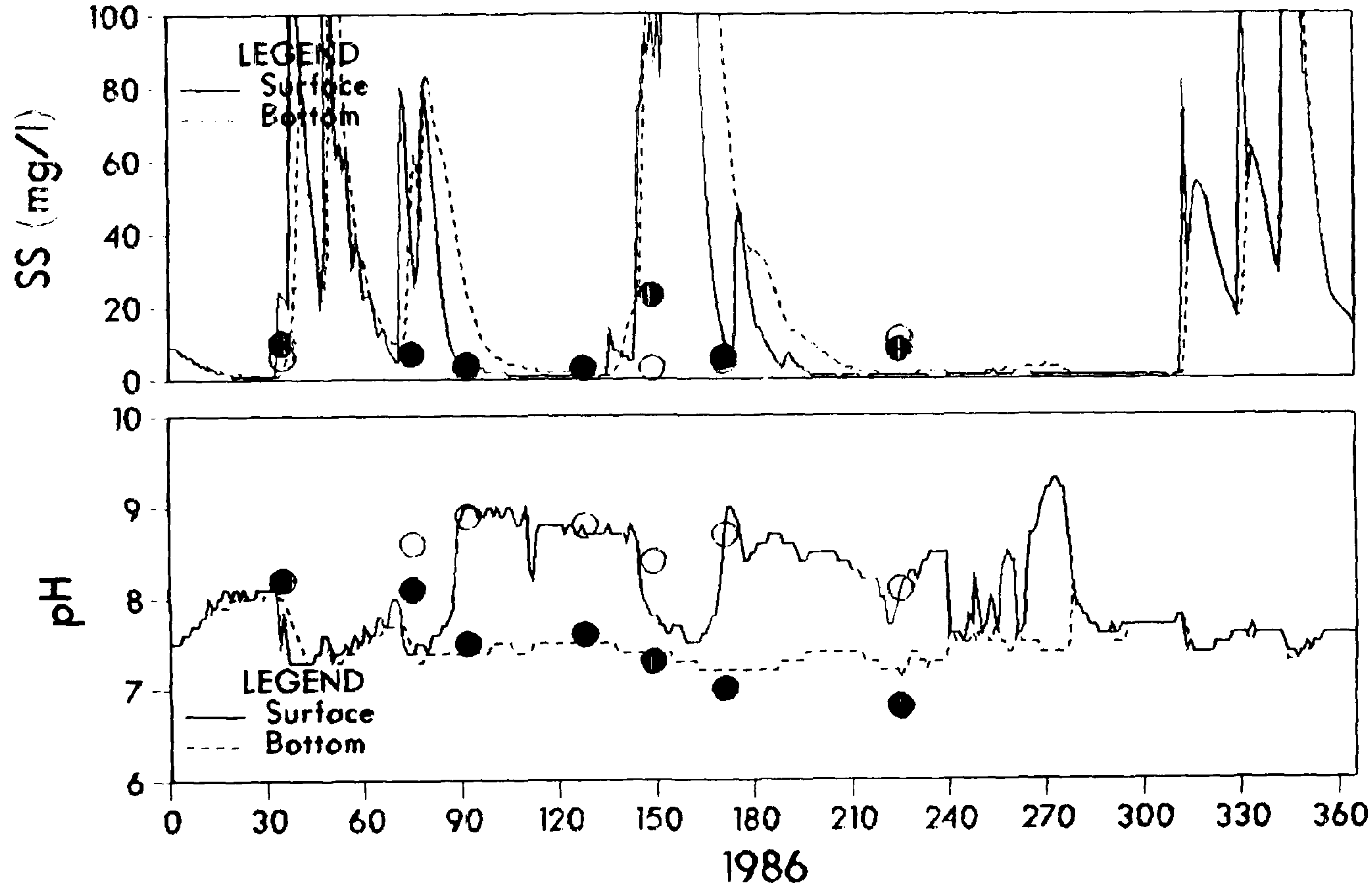


Figure 38   Validation Results at Eddy Creek Mile 2.2 for 1986

EDDY CREEK EMBAYMENT MILE 2.2



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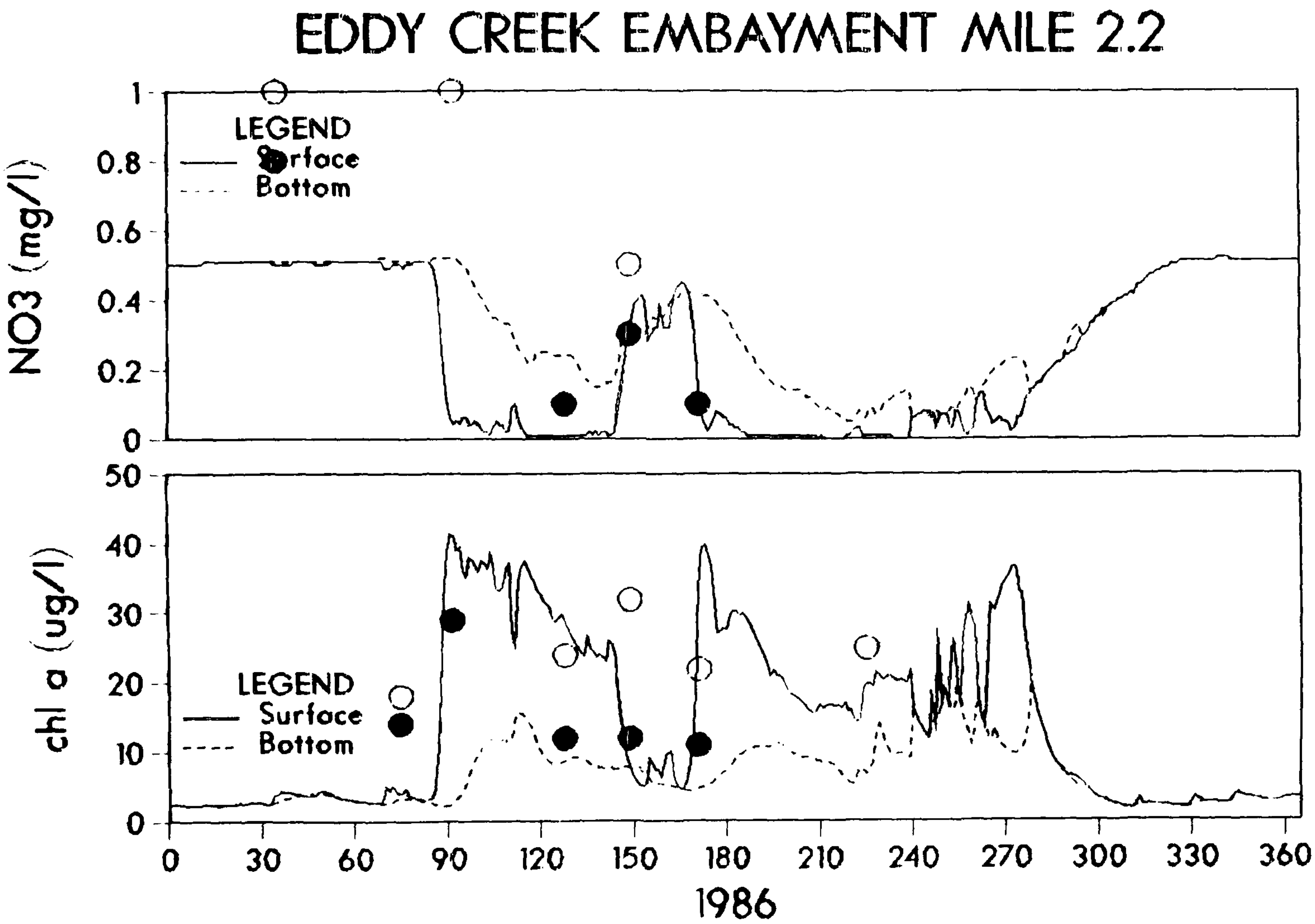

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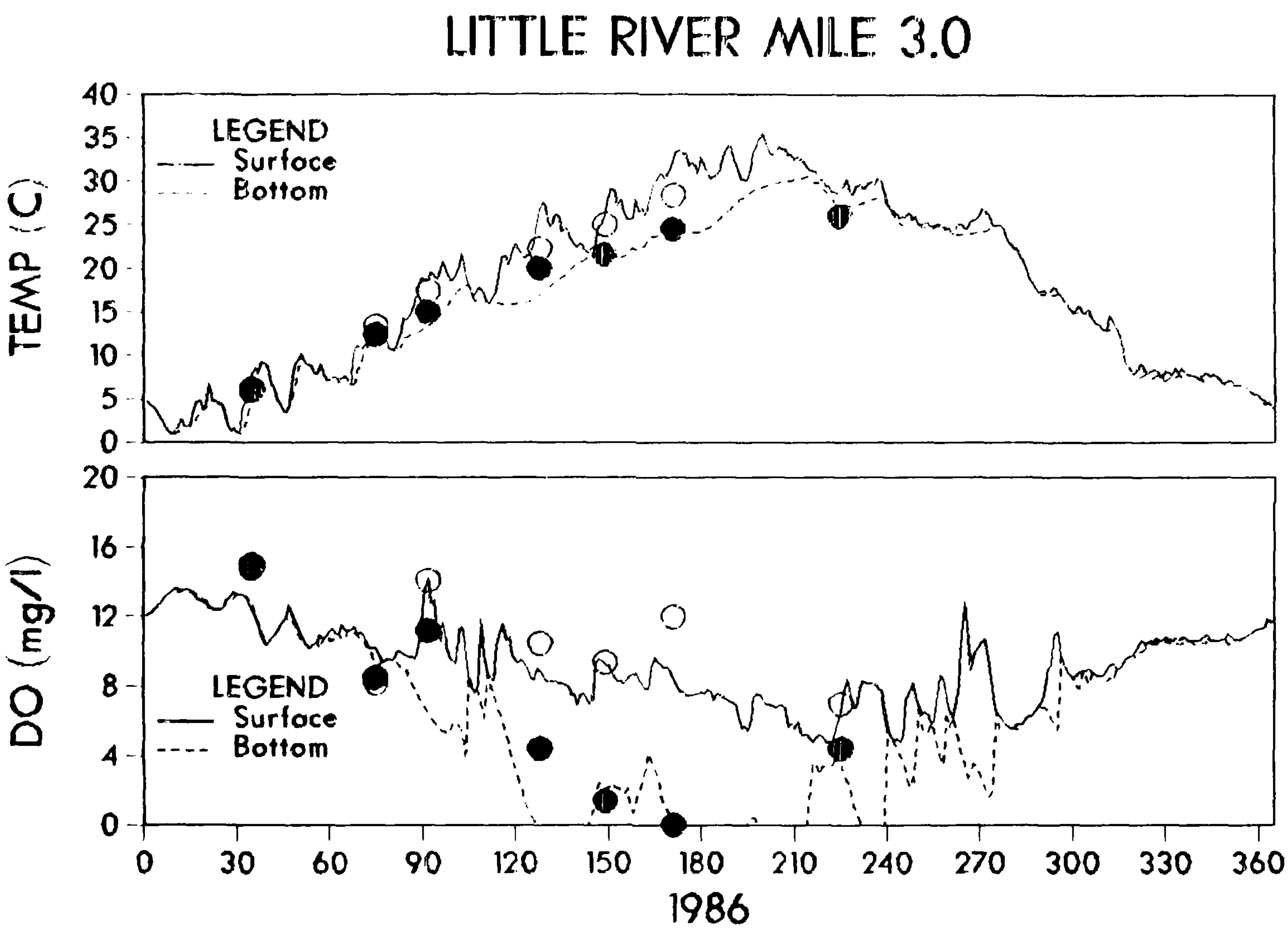


Figure 39 Validation Results at Little River Mile 3.0 for 1986

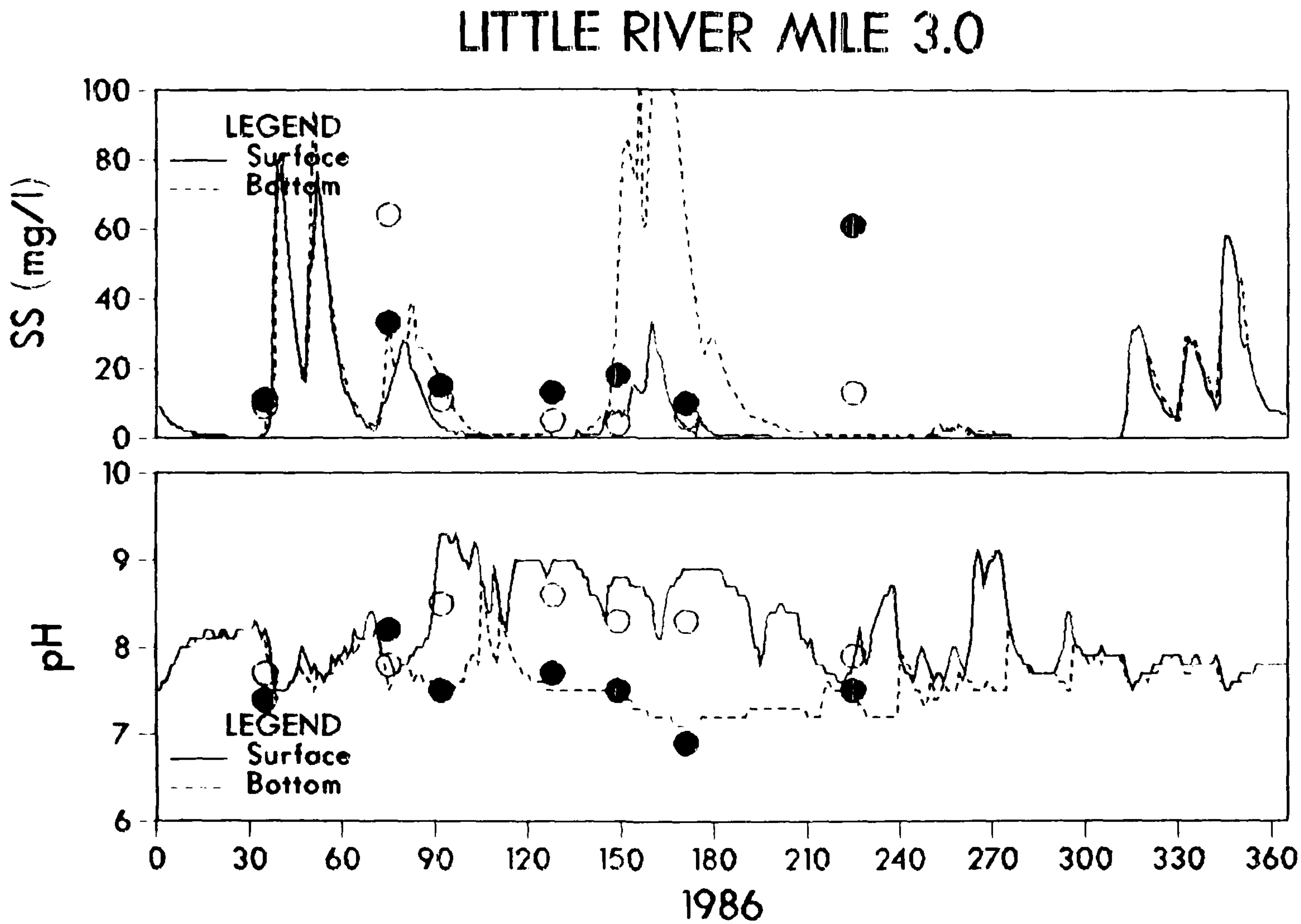


Figure 39 (continued)

LITTLE RIVER MILE 3.0

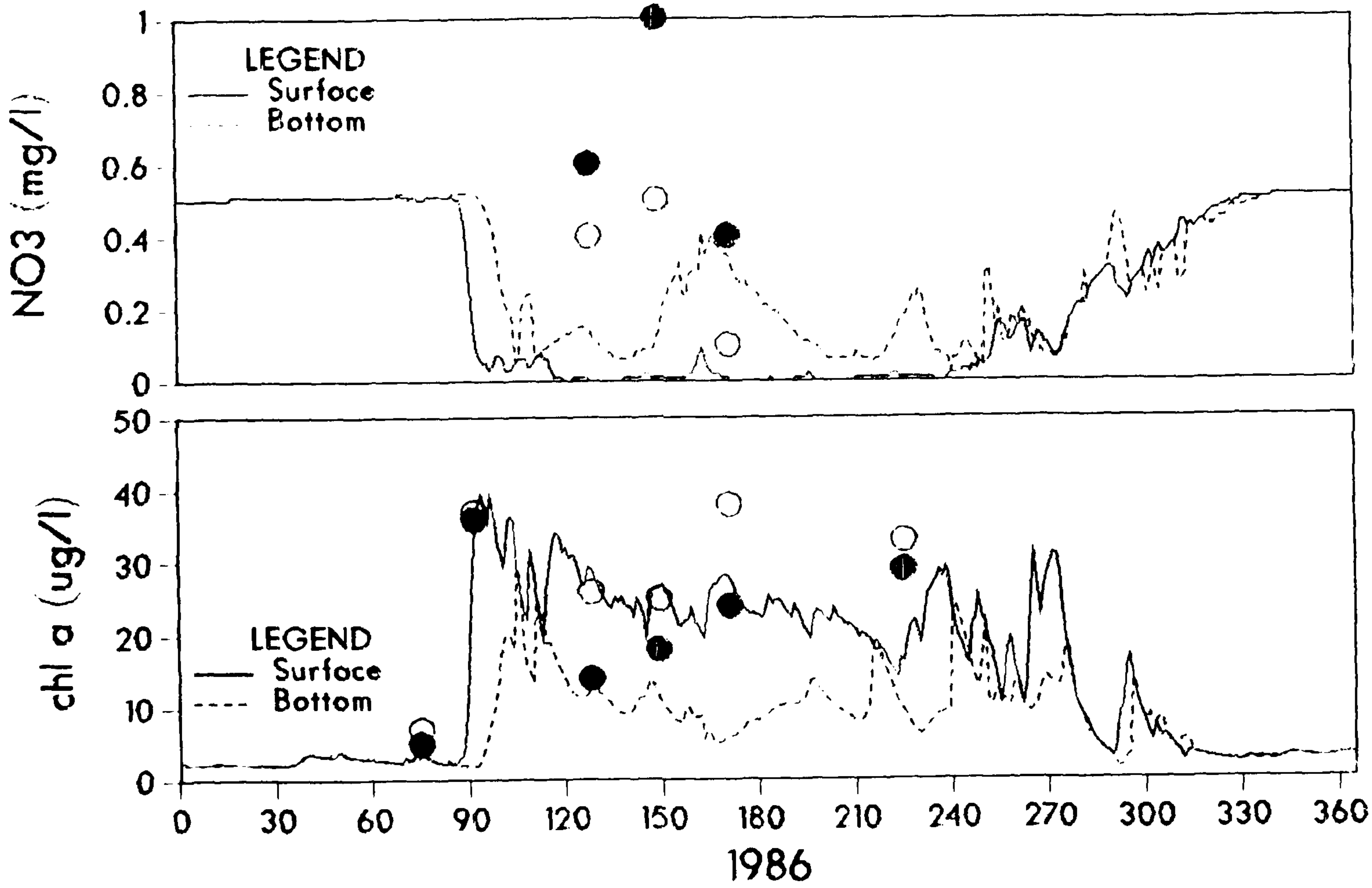


Figure 39 (continued)

Figure 40 Modeled Surface Temperature Patterns for 1986

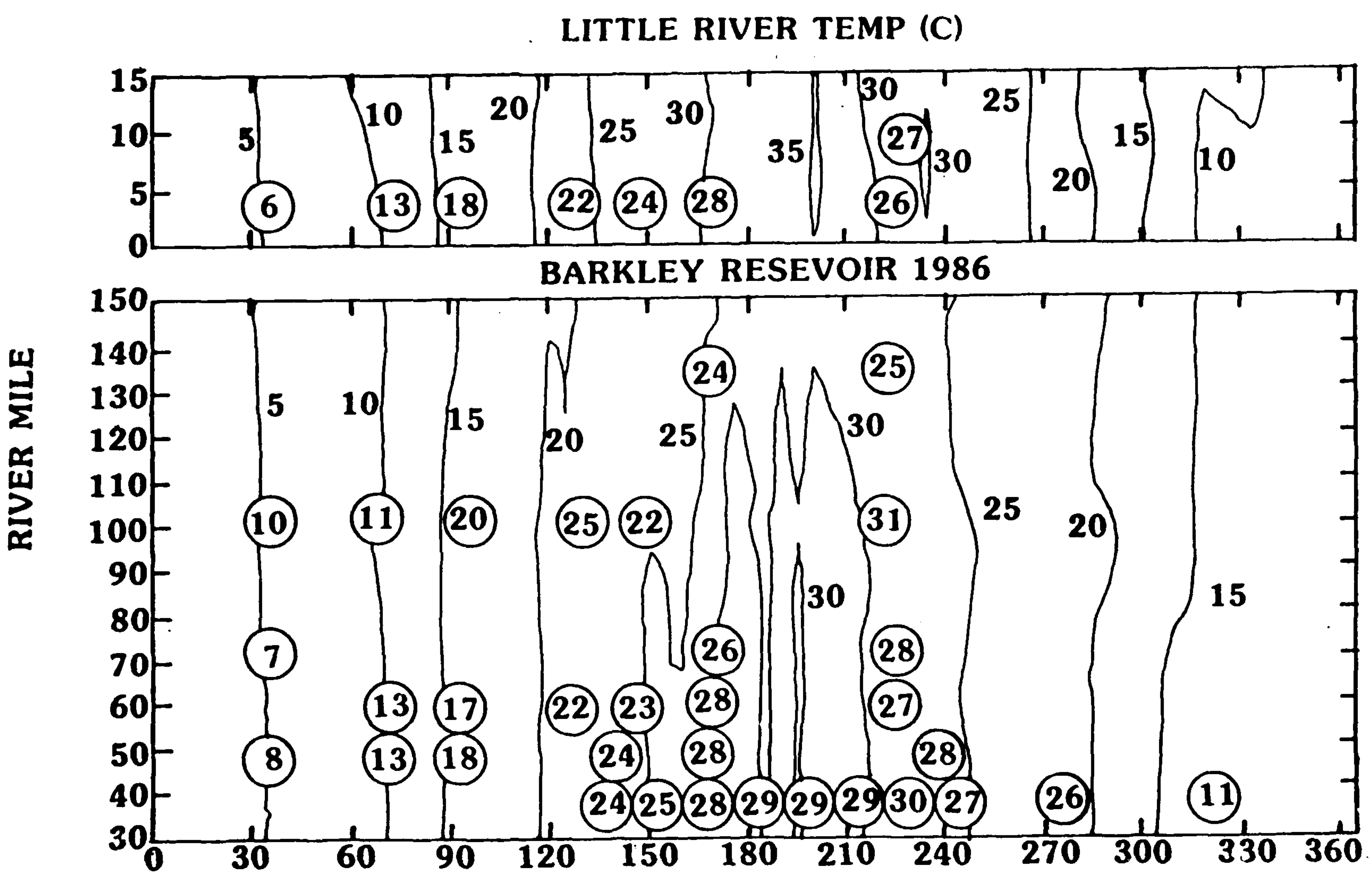
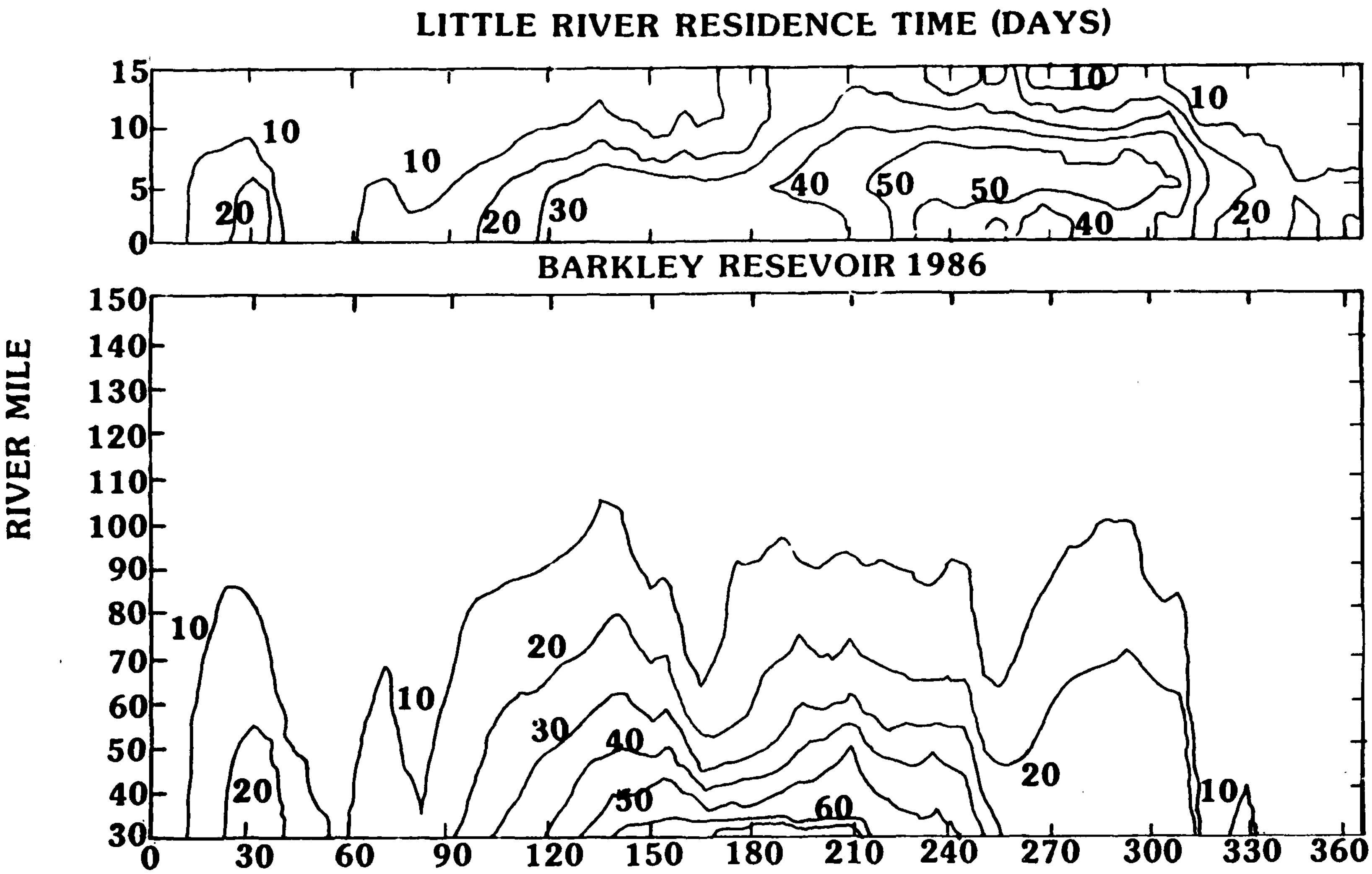


Figure 41   Modeled Surface Residence Time Patterns for 1986



had increased residence times caused by the lower flow conditions in the Cumberland River. The residence times in 1985 were unusually high in April, decreased with a major inflow event during May, and increased again to a maximum in June and July. Regulated flows during August were increased so the residence times decreased for a period, but increased again in October. The 1986 residence time pattern had very low spring flows with extremely long residence times until some moderate flows occurred in early June. Residence times remained very constant at more than 30 days through the summer and fall, with the surface layer residence times considerably longer due to stagnation caused by stratification. Although these residence time patterns cannot be validated with field data, they correspond with the water budget calculations shown in Figure 13. These residence time patterns were quite helpful for interpreting the extreme stratification and DO depletion patterns simulated by the model for 1985 and 1986.

Dissolved Oxygen Validations

Surface DO supersaturation caused by algal activity was commonly observed at all stations, as was DO depletion during stratified conditions. The model simulations indicated that the magnitude of the DO depletion was governed by the duration of the intermittent stratification periods.

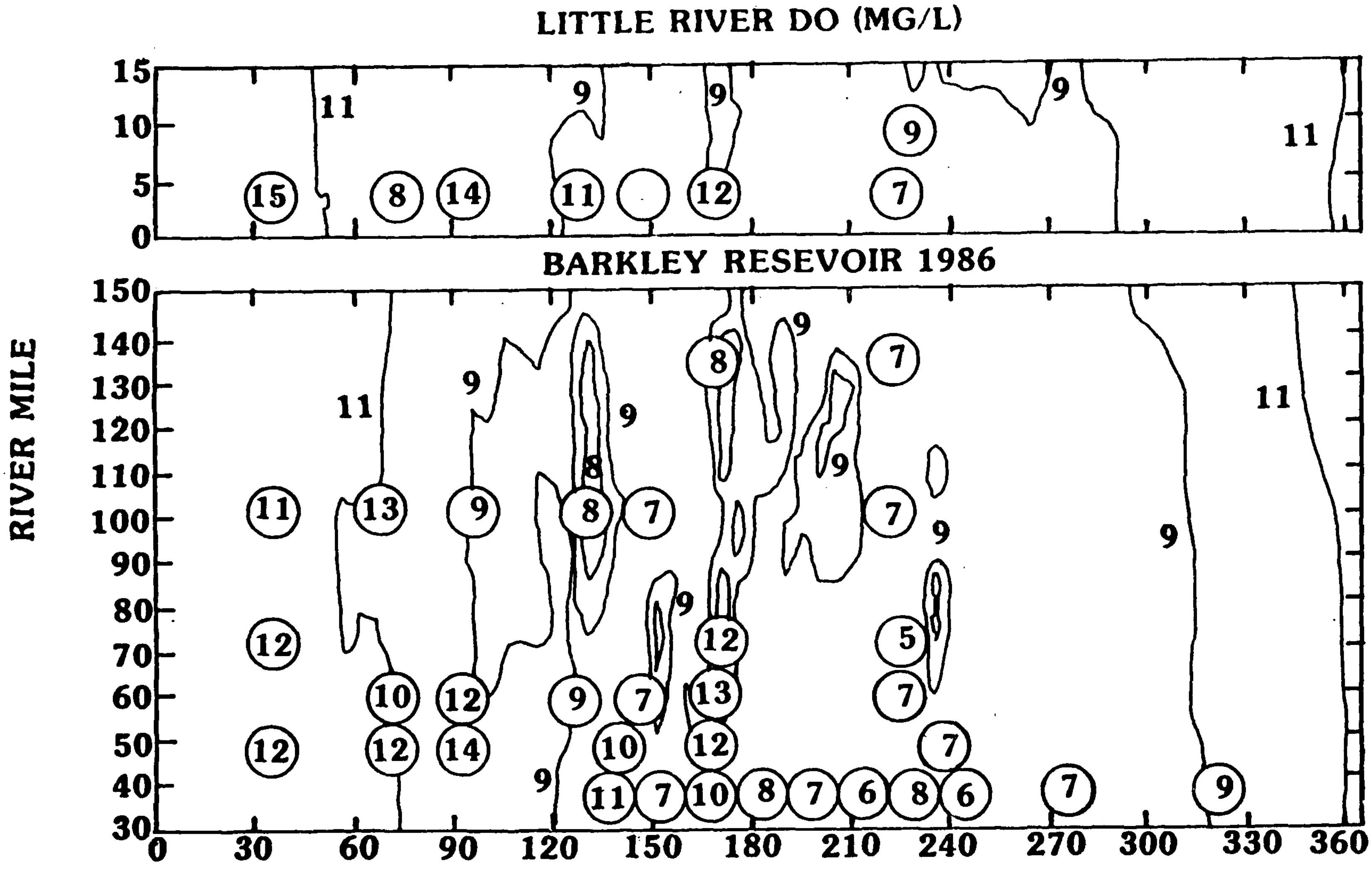
Mixing had a strong effect on DO patterns. For example, the third survey during 1985 indicated that a strong cooling event had caused mixing at CuRM 58.2 and Little River, but not at CuRM 41.5 and Eddy Creek. This was because these pairs of stations were actually sampled three days apart, with CuRM 41.5 and Eddy Creek sampled on June 10, while the other stations were sampled on June 13. On June 10 there had been a long stratification period during warming meteorological

conditions, and DO depletion was significant at the bottom of the sampled stations. Cool meteorology and significant rainfall during the next few days caused considerable surface cooling and vertical mixing, so that the stations sampled on June 13 had much less stratification and DO depletion. Although the model did not exactly reproduce this mixing event (using meteorology from Paducah), the model did simulate vertical mixing slightly later in June, caused by the cooler meteorological conditions and the increased flows that accompanied this June storm.

Surface DO patterns, shown in Figures 31 and 42 indicated more patches of DO supersaturation. These occurred farther upstream than in 1984, corresponding to the lower flows and lower SS concentrations during these two years. These patches of high DO concentrations were restricted spatially by the uptake of nutrients which limited algal productivity, and temporally by aeration processes which reduced the DO concentrations to near saturation values.

Because Barkley Lake is intermittently stratified, more frequent data collection efforts will be required to accurately measure the water quality changes during a sequence of warming conditions which cause stratification and cooling, wind mixing, and increased flow conditions, which cause vertical mixing. Automatic temperature, DO and pH monitors at the surface and bottom of a station could be utilized to record this type of data. The model predictions at the four key stations during 1985 and 1986 demonstrated the intermittent DO depletion patterns that occur during stratified periods in Lake Barkley, and were generally confirmed by the available periodic data.

Figure 42 Modeled Surface DO Patterns for 1986



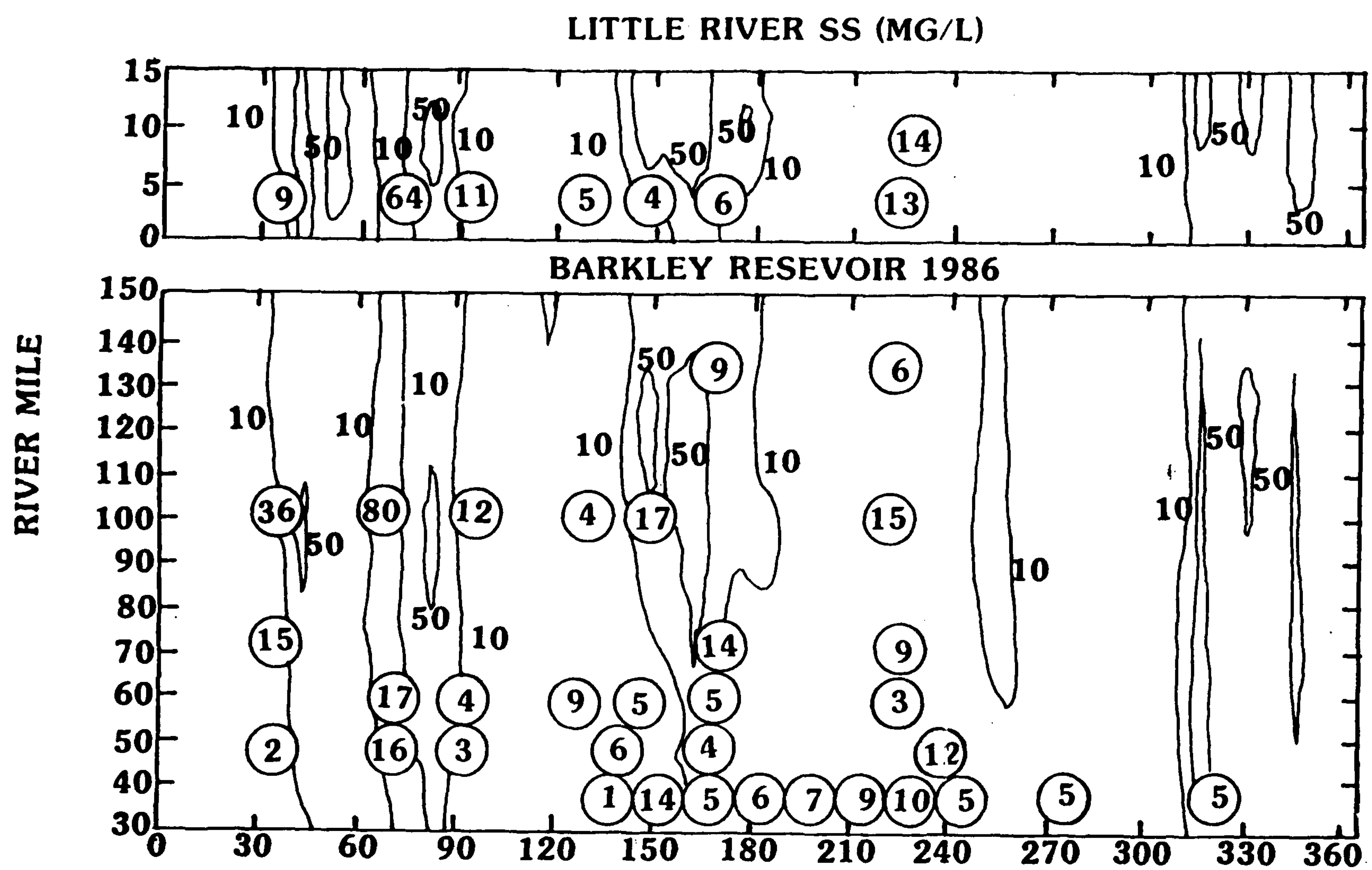
Suspended Sediment Validations

The available SS data for 1985 and 1986 indicated that the model underestimated the SS concentrations at almost all the stations for both years. Simulated SS concentrations during the stratified period were below 10 mg/L except following storm inflows in May and June of 1985 and June of 1986. But the field data indicated that surface SS concentrations remained between 10 and 20 mg/L, while bottom concentrations were much higher at 20 to 50 mg/L. This is curious since the 1984 calibration simulations matched the available SS data, which indicated that surface SS concentrations decreased to 10 mg/L during stratified conditions.

The simulated surface SS patterns for 1985 and 1986 are shown in Figures 32 and 43. Very few high SS periods occurred during 1985, so that light conditions were ideal for most of the year. Several large storms with high SS concentrations occurred during 1986, but most of the growing season was clear. A significant inflow of SS in June of 1986 transported high SS concentrations almost to the dam, interrupting the ideal light conditions and limiting algal growth.

Apparently there are particulates remaining in the water column which the modeled settling rate of 0.5m/day removed from the reservoir during these longer residence time periods. This material might have been organic particles produced within the reservoir, which were not measured as inflowing turbidity, and so were not included in the modeled SS patterns. Since the light conditions which result from adsorption by these particulates are quite important for algal productivity, more specific data collection to document the transport and settling of particulates in Lake Barkley is suggested. A field sampling survey using a turbidometer probe might be initiated following a significant inflow of SS

Figure 43 Modeled Surface SS Patterns for 1986



materials, as measured by turbidity at the Clarksville water intake, to document transport and settling patterns within Lake Barkley.

Nitrate, pH, and Chlorophyll Validations

Very little data were collected for pH, nitrate and chlorophyll in 1986, but the 1985 data were quite extensive, and provide a good chance to validate the model algorithms for nutrient uptake and algal biomass production.

Simulated pH patterns indicated increased algal productivity prior to the first measurements in late May of 1985, with surface values between 8 and 9 throughout the stratified period. The model simulated several vertical mixing episodes between measurement dates, and the vertical pH gradients were not always matched, but the simulated pH patterns generally followed the measured pH data quite well. The modeled release of CO_2 from the sediment was helpful in keeping the bottom pH values near 7, which matched the bottom pH data. Matching surface pH measurements with the daily average simulations was difficult since diurnal pH variations were significant.

The simulated chlorophyll patterns generally followed the measured values, with 20 to 40 $\mu g/L$ predicted during the growing season. Only in November of 1985 and March of 1986 were chlorophyll values below 20 $\mu g/L$. The simulated seasonal growth of algae appears to be reasonable in comparison to the available measurements. The effects from light limitation may not have been properly modeled since the simulated SS patterns were too low, although the minimum extinction of 1.0 m^{-1} accounts for some of the light extinction from these particulates.

The nitrate uptake patterns matched the measured values well during 1985, except that there were occasional high measured values which do not appear

consistent with the other data or the model simulations. The model indicated that much of the nitrate was used for algal growth in the main channel and the embayments. The inflow ratio of nitrate to phosphorus was 50, while the simulated algal biomass content ratio was 15, so that phosphorus was never the limiting nutrient in these simulations of algal growth.

The surface patterns of nitrate, pH, and chlorophyll provide perhaps the clearest illustration of the simulated algal patterns. These are shown in Figures 33 to 35 for 1985, and Figures 44 to 46 for 1986. During 1985 the simulated pH contour of 8 delineates the algal growth "window", which extended almost the entire length of the reservoir from late April through September. Periodic vertical mixing events interrupted these ideal growth conditions. Nutrient uptake occurred within this window, with complete use of nitrate simulated in the downstream portion of the lake from May through August. High chlorophyll values were simulated during this same period. The high chlorophyll was apparently diluted by the discharge of cooling water from the bottom at the Cumberland Steam Plant near CuRM 103.

The high pH values (above 8) were simulated earlier in 1986, extending the entire length of the lake by the end of April. The 1986 nutrient uptake patterns were similar to 1985, with complete nitrate depletion as far upstream as CuRM 125. These uptake and growth patterns were pushed downstream by the high June inflow and then moved back upstream later in the summer. The duration and upstream extent of chlorophyll was much greater during 1986 than for the previous two years, and perhaps represents the most extreme conditions to be expected in Lake Barkley for current inflow nutrient conditions. The available data

Figure 44 Modeled Surface pH Patterns for 1986

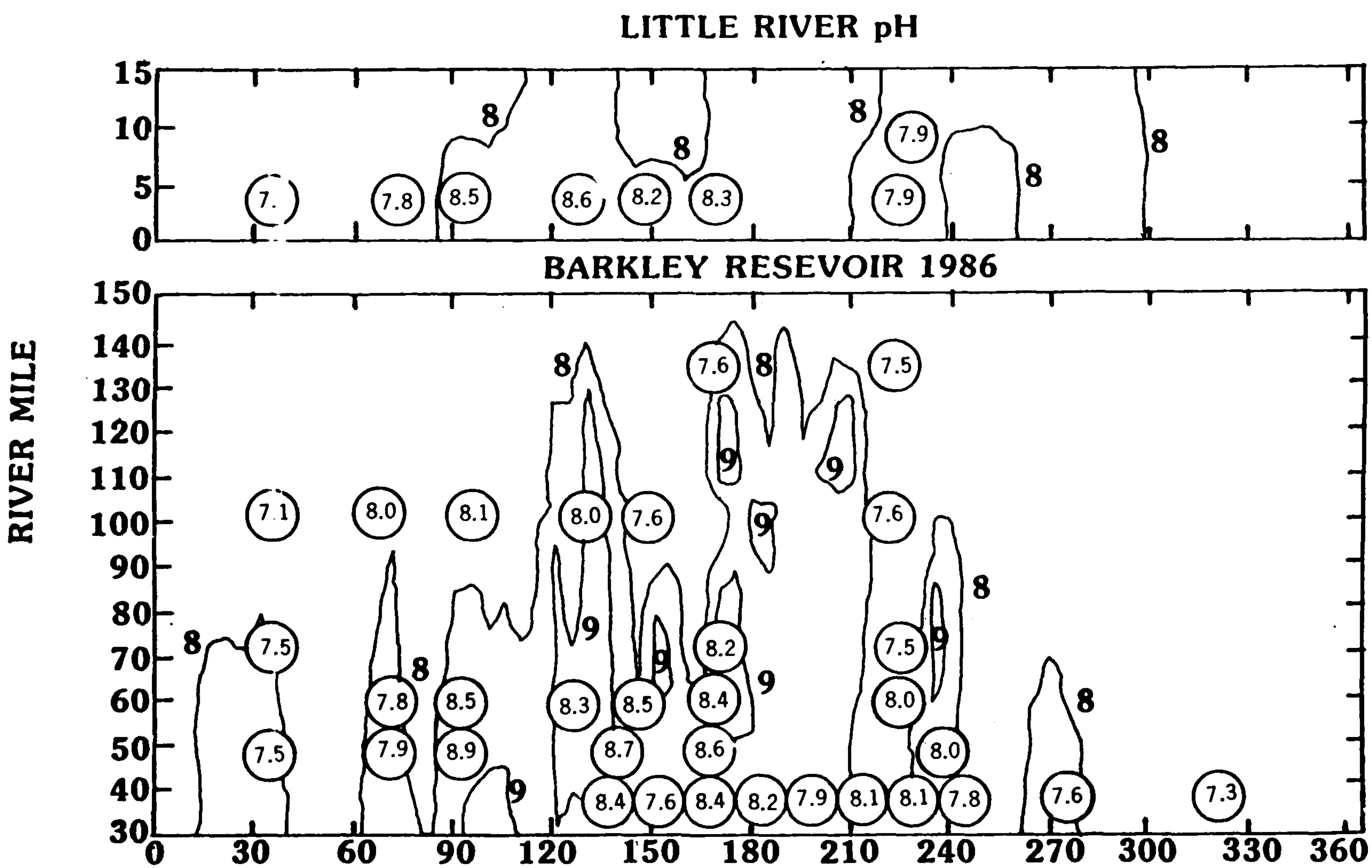


Figure 45 Modeled Surface Nitrate Patterns for 1986

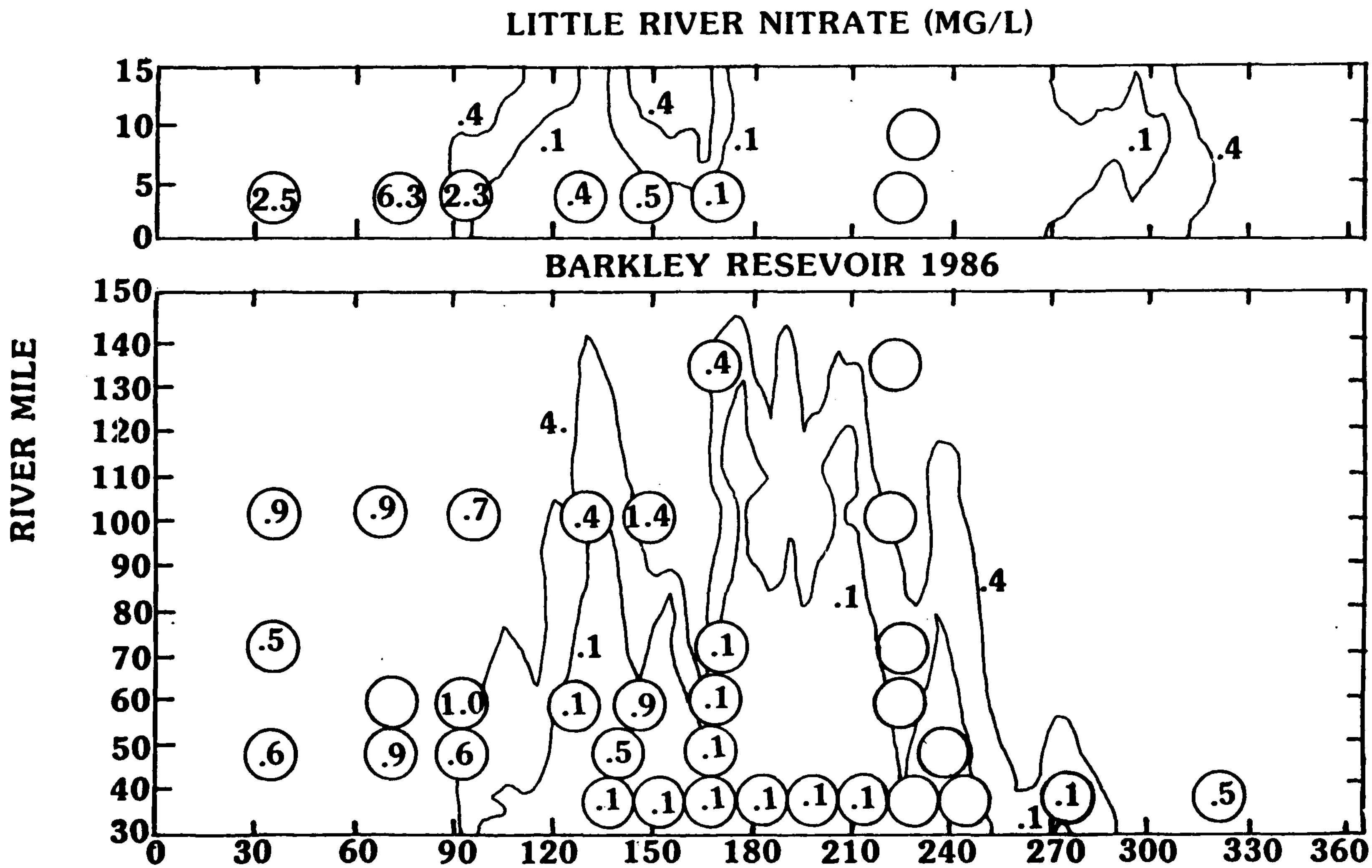
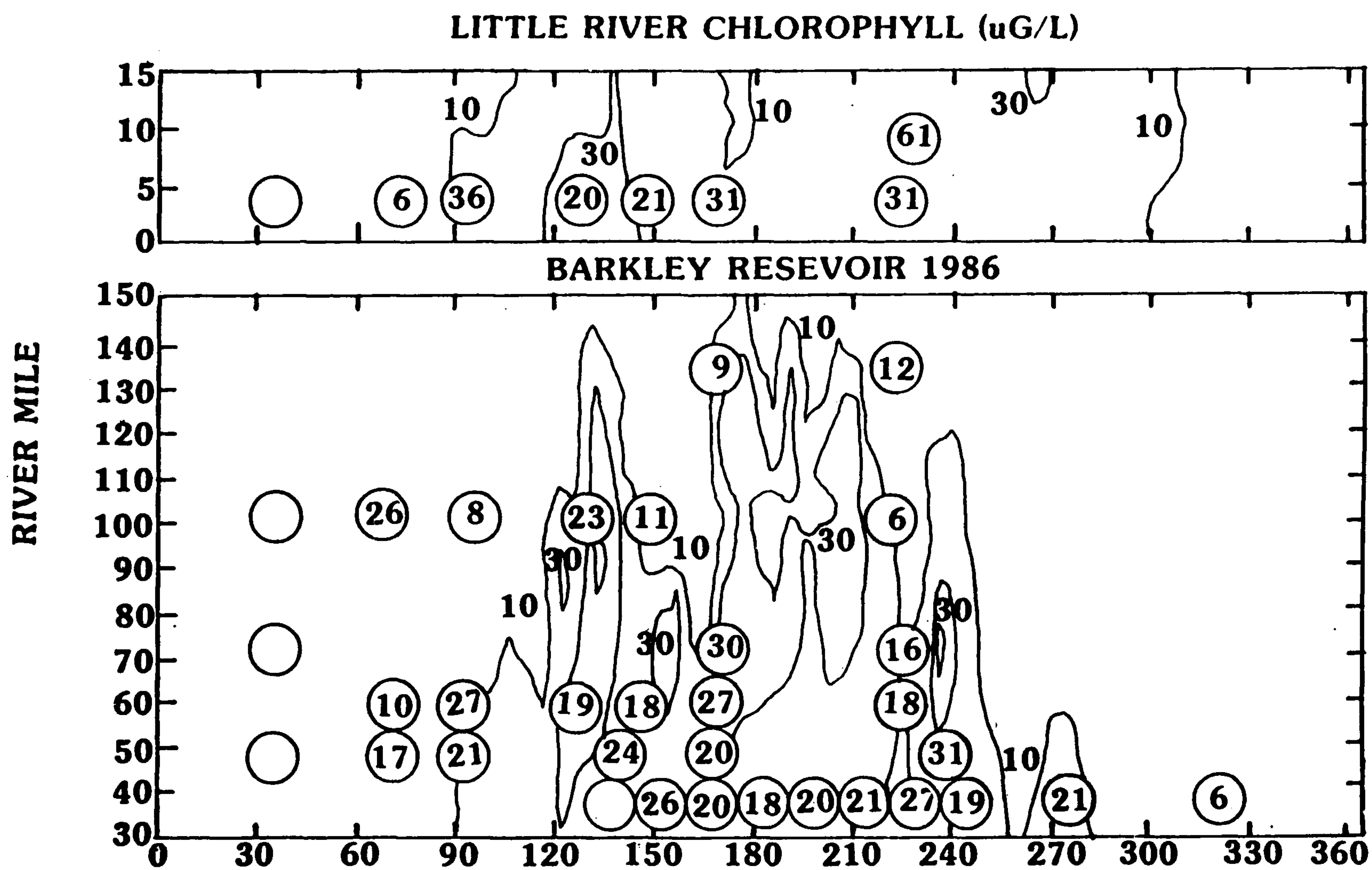


Figure 46   Modeled Surface Chlorophyll Patterns for 1986



generally confirm these simulated patterns of nutrient uptake and algal growth for 1985 and 1986.

SENSITIVITY OF WATER QUALITY IN BARKLEY LAKE

These calibration and validation results gave confidence in the simulations of a variety of cases that are of interest for water quality planning and management controls for Lake Barkley. Two of these sensitivity cases were requested in the scope of work from the Corps of Engineers: 1) effects from increased loadings of organic materials and nutrients from point and non-point sources, and 2) effects from major summer storm events. Several additional simulations were made to identify the sensitivity of Lake Barkley water quality to model parameters and inflow conditions. The year 1985 was chosen for these simulations to evaluate effects during low flow conditions.

Effects of Increased Inflow Loadings

The inflow load of organic material was increased to the equivalent of 2.5 mg/L of BOD during the calibration of the DO patterns. The sensitivity of modeled DO depletion patterns to organic loading was tested by simulating two additional cases for 1985: 1) 0.0 mg/L BOD inflow from all sources, and 2) 5.0 mg/L BOD from all sources. These cases are shown in Figure 47 for the four key stations. The solid lines represent surface and bottom DO concentrations for the sensitivity run, while the dashed lines represent the base case simulations. The increased inflow loads of BOD decreased the bottom DO concentrations during the stratified periods, but had little effect on surface concentrations. The magnitude of the decrease depended on the duration of the stratification period, with a maximum simulated decrease in bottom DO of 1-2 mg/L. A small increase

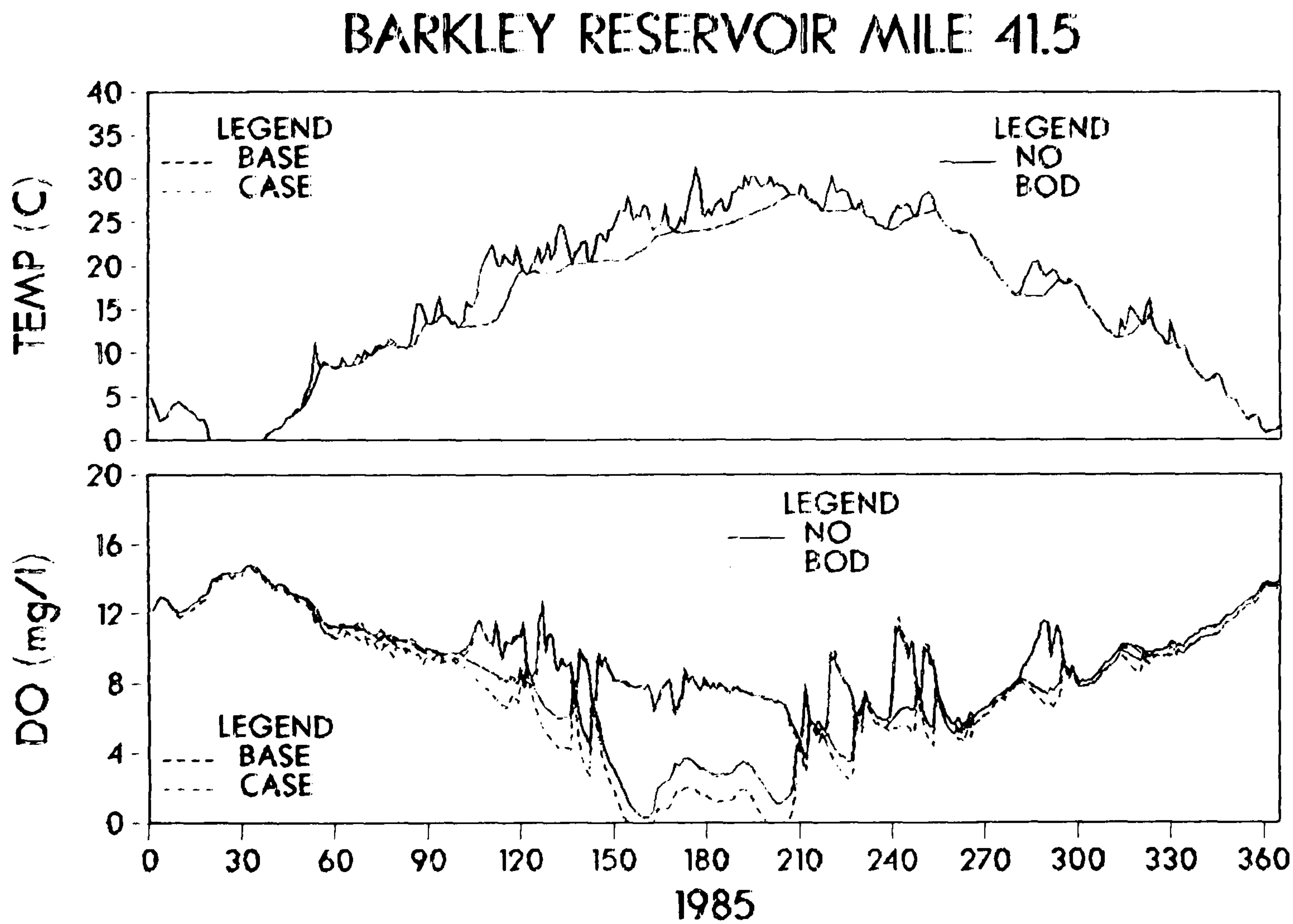


Figure 47 Simulated Effects of Reduced Organic Loading (0 mg/L BOD)

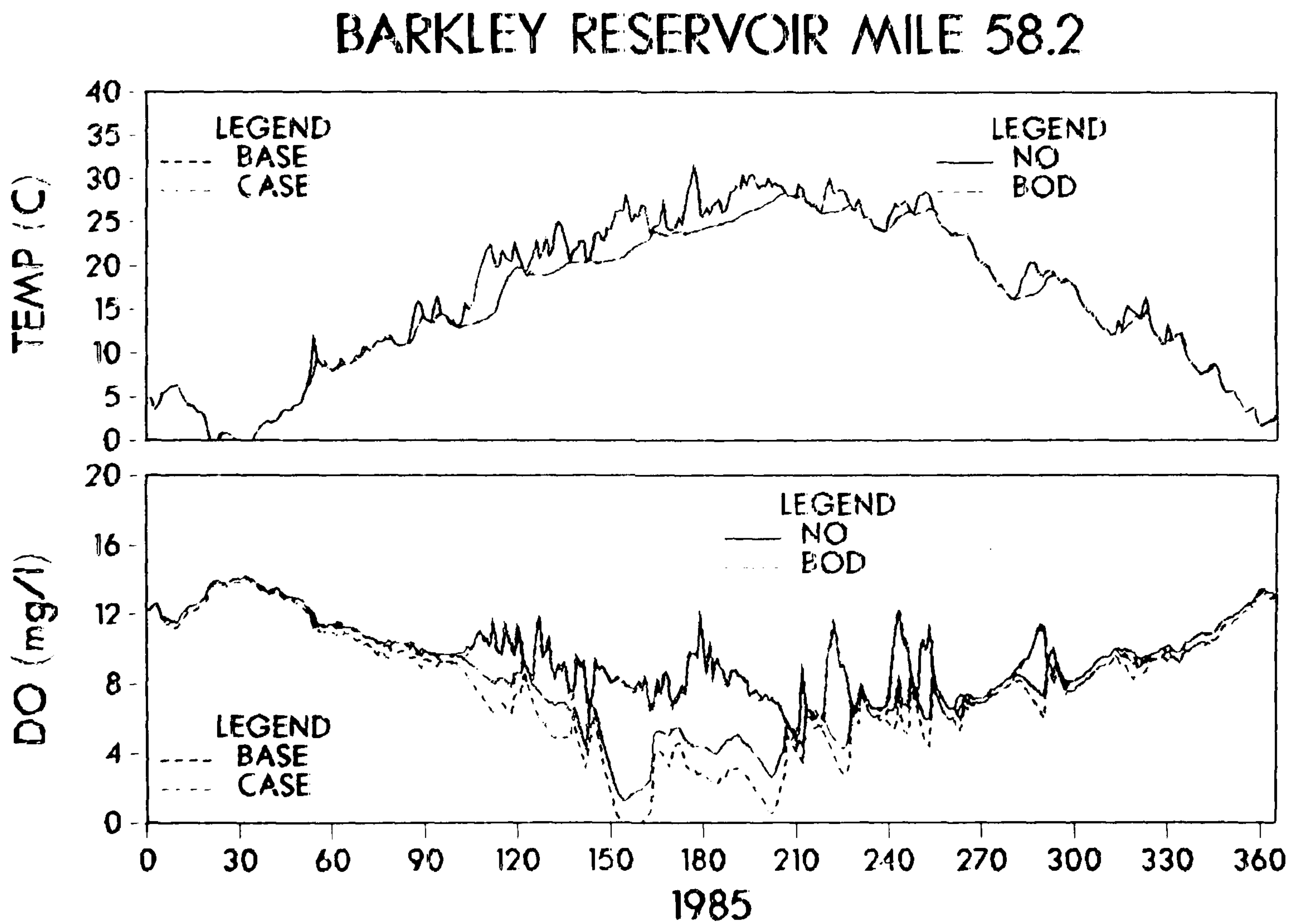
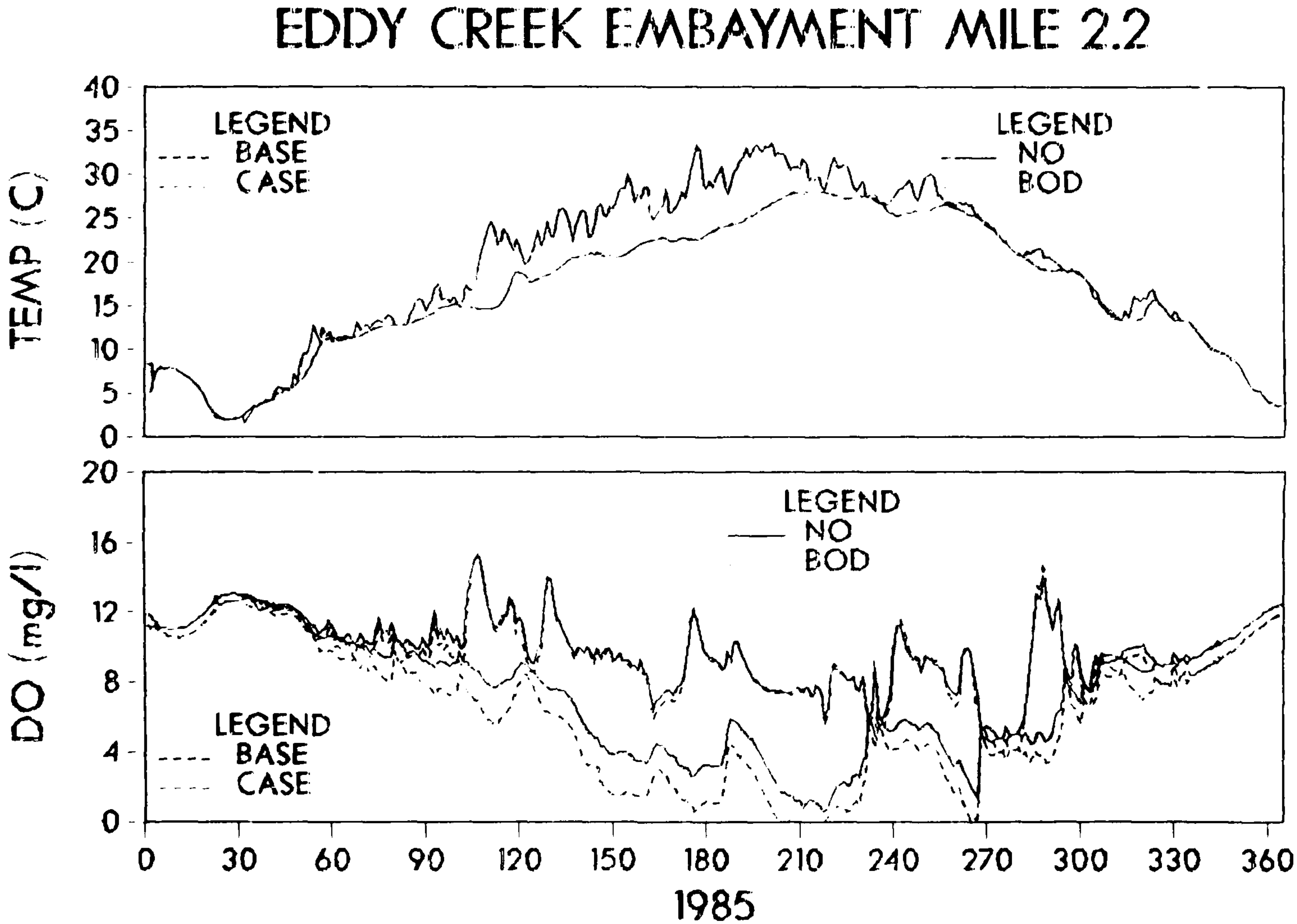


Figure 47 (continued)



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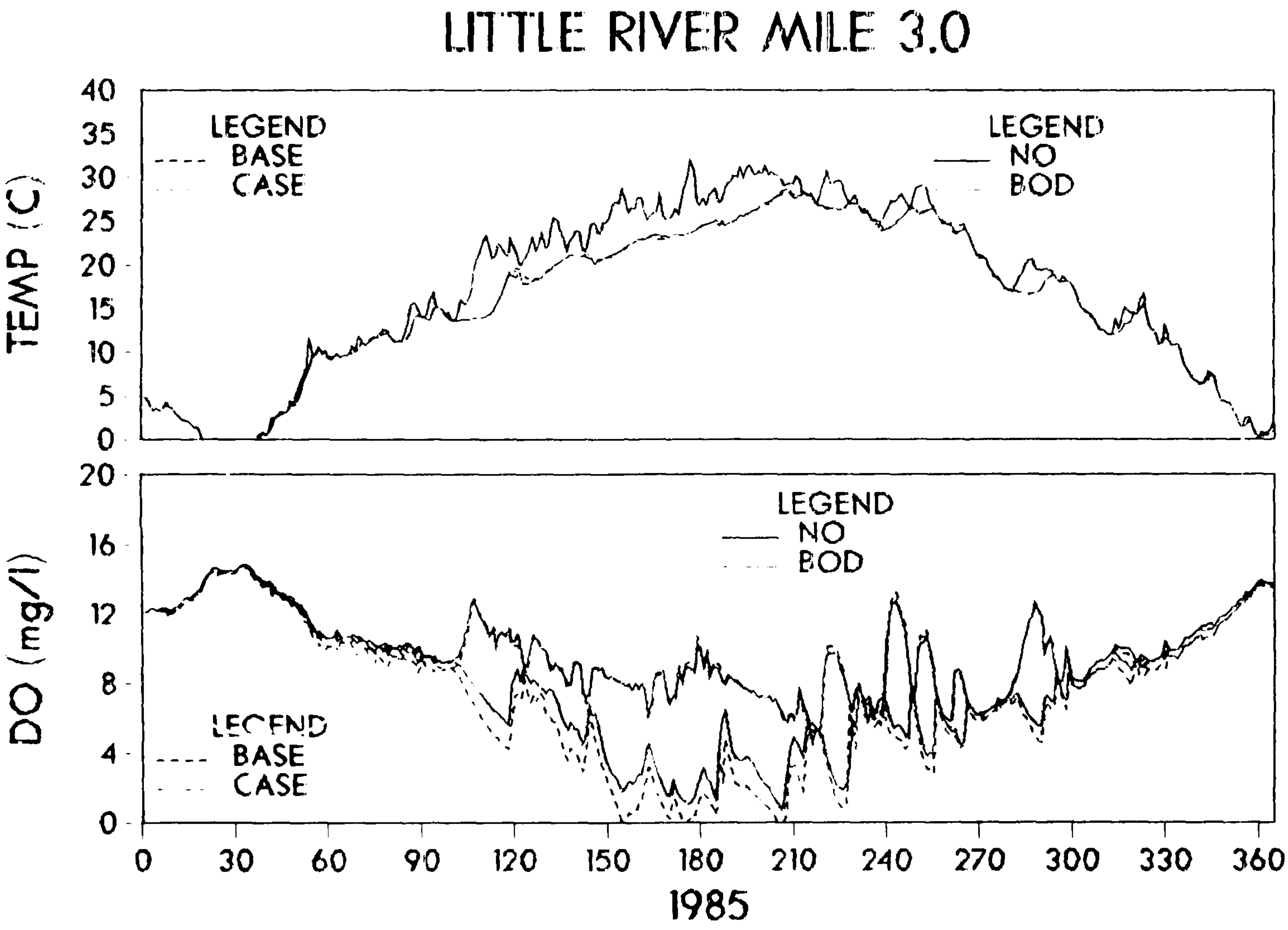


Figure 47 (continued)

in chlorophyll was also simulated, since the model split the BOD into detritus and dissolved organics, and the detritus had nutrients associated with it.

A second case was simulated with the BOD inflow set at 0.0, to determine the magnitude of the DO depletion that was caused by the inflowing organic materials. The results at the four stations are shown in Figure 48. The increase in bottom DO concentrations were similar to the decrease from higher BOD inflows, with a maximum increase of 1-2 mg/L. These results indicated that inflowing BOD can have an observable effect on bottom DO during stratified conditions. More accurate estimates of inflowing organic loads are needed to eliminate this source of modeling uncertainty.

Effects of Major Summer Storm Runoff Events

A sequence of summer storms were simulated from April through October of 1985. One inch runoff events were superimposed onto the actual inflows and outflows on days 125, 150, 175, 200, 225, 250, 275, and 300. This represents 8 inches of additional summer runoff, which is an extreme case for sensitivity testing purposes only. Each storm was assumed to occur over the entire local watershed, with a three day unit hydrograph (0.6, 0.3, and 0.1). The assumed storm quality was: 10 mg/L BOD, 250 mg/L SS, 1.0 mg/L nitrate, and 0.1 mg/L phosphorus. No changes were made in the meteorology, although major storms would generally occur with cooling meteorological conditions. The simulated effects are shown in Figures 49 to 52. The effects from each storm inflow event depended on the lake water quality conditions at the time of the storm.
During mixing periods, the extra flows and organic loads had a relatively minor effect. But during stratified conditions, the extra organic and nutrient loads produced observable changes in the simulated water quality patterns.

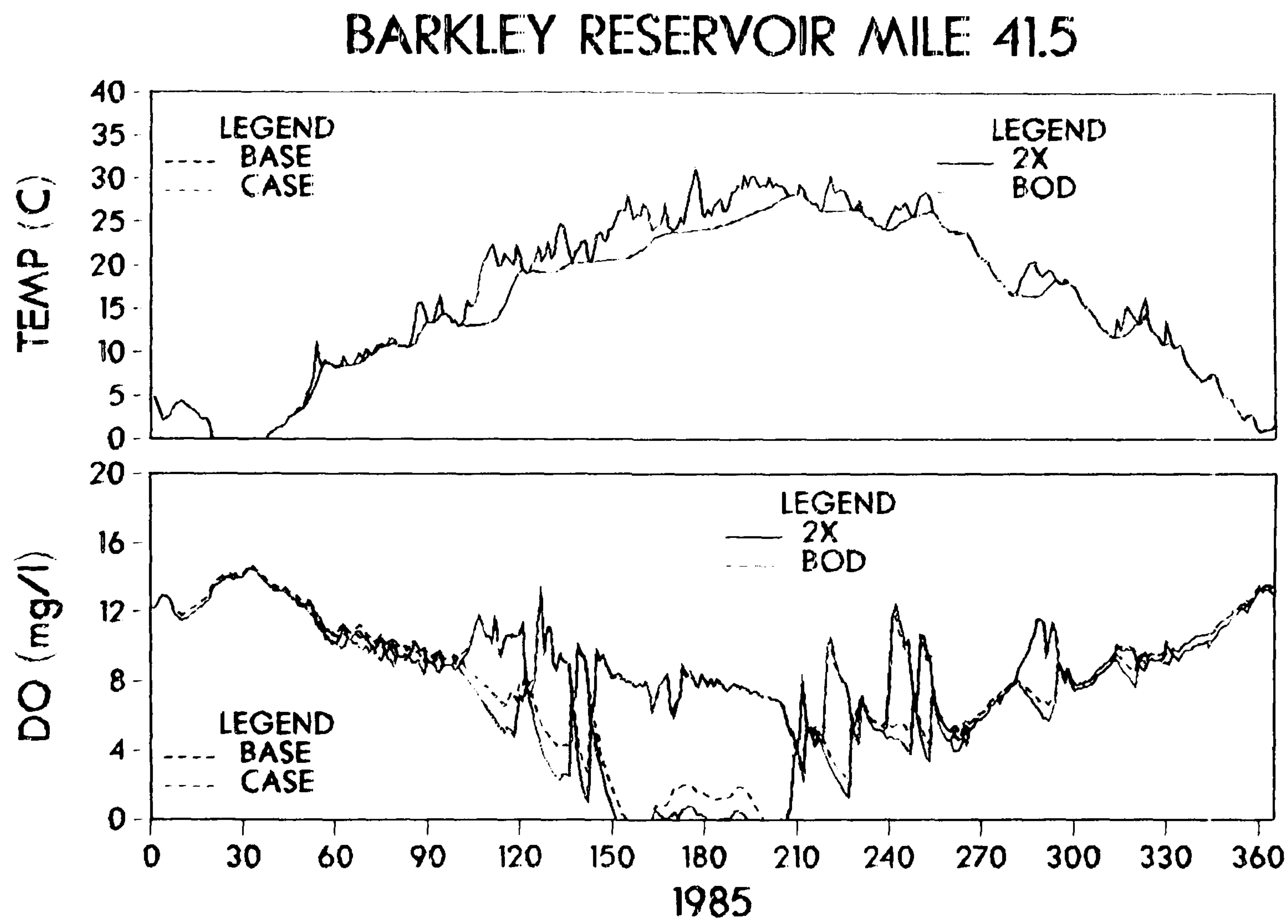


Figure 48 Simulated Effects of Increased Organic Loading (5 mg/L BOD)

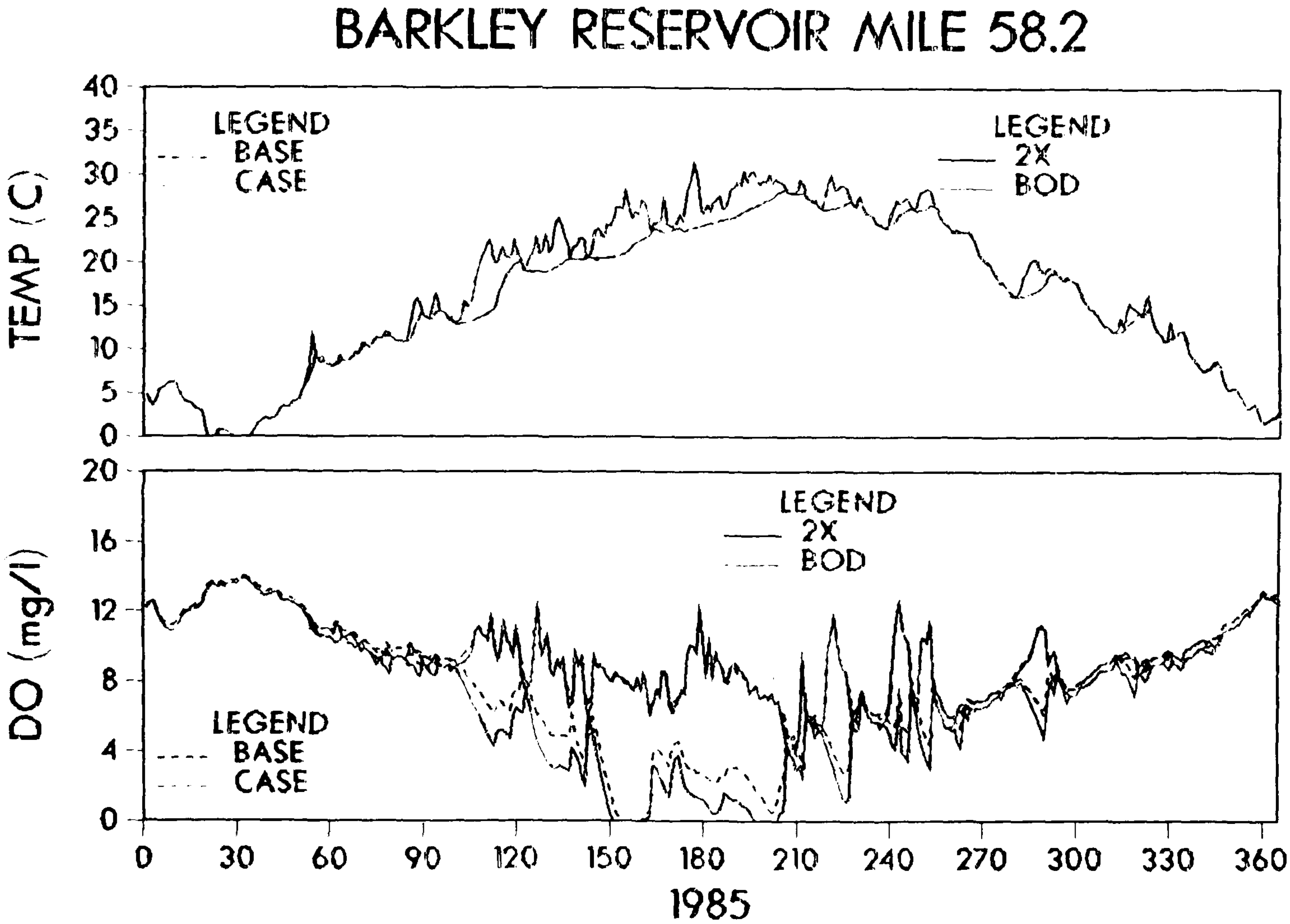


Figure 48 (continued)

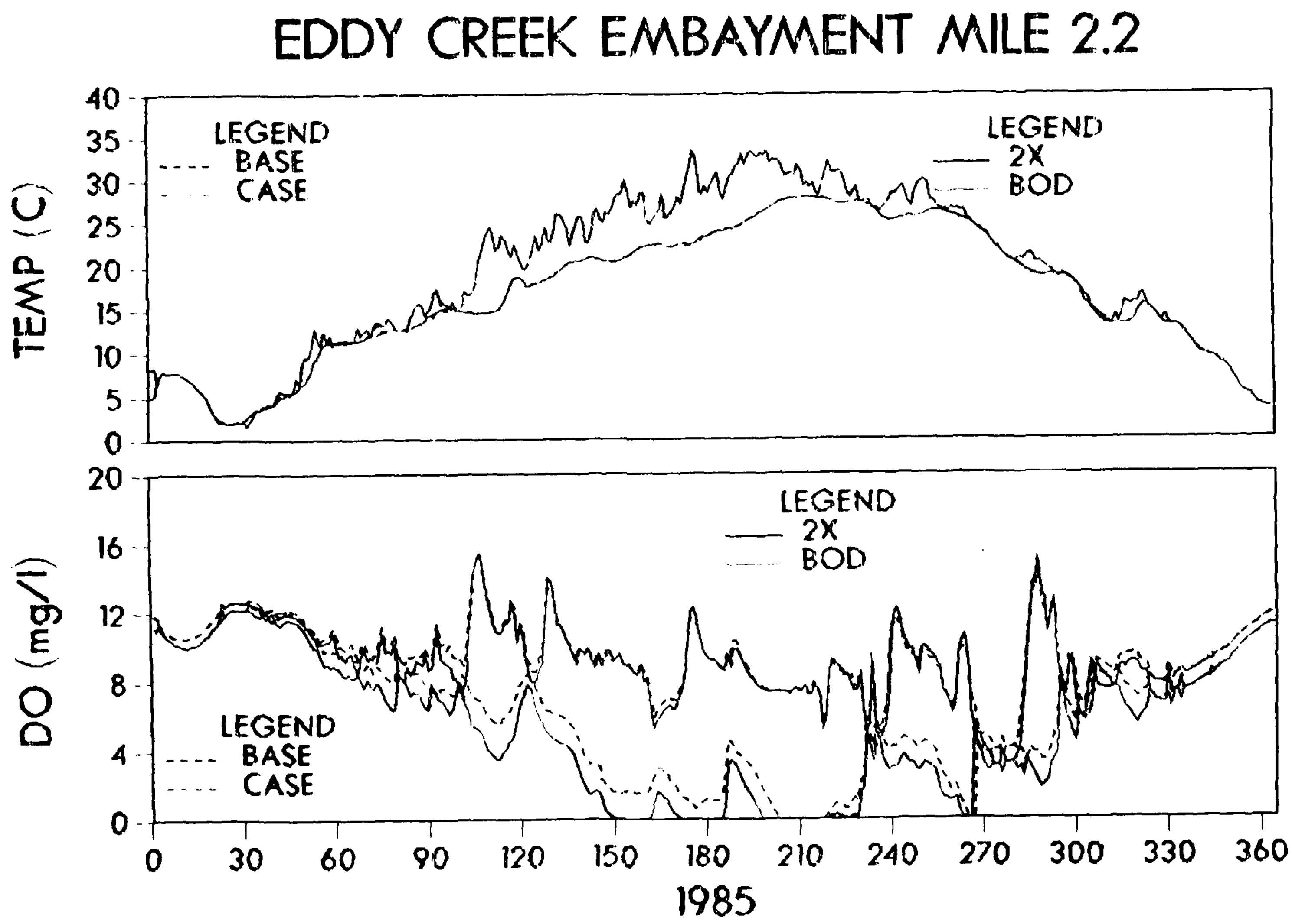
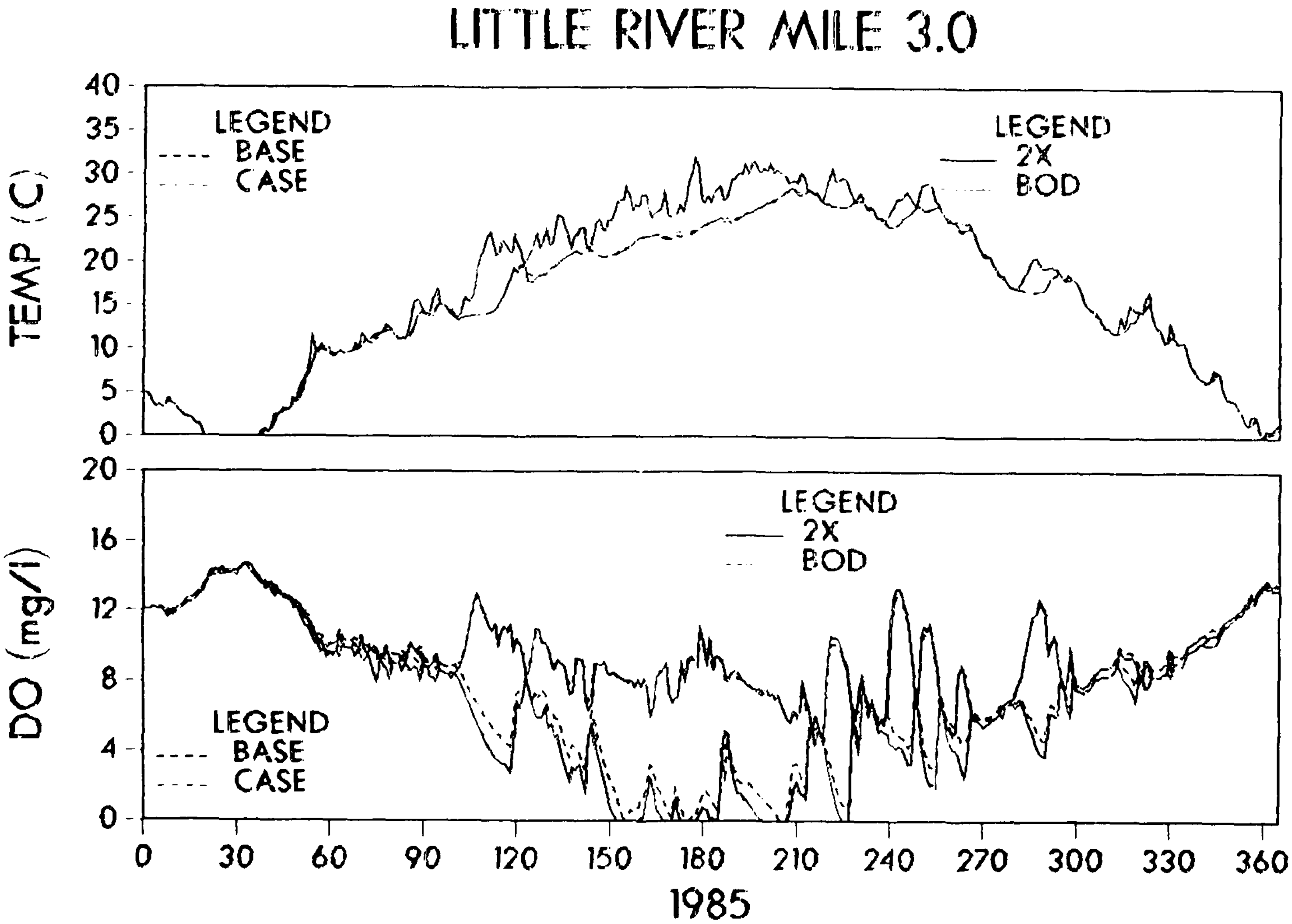


Figure 48 (continued)



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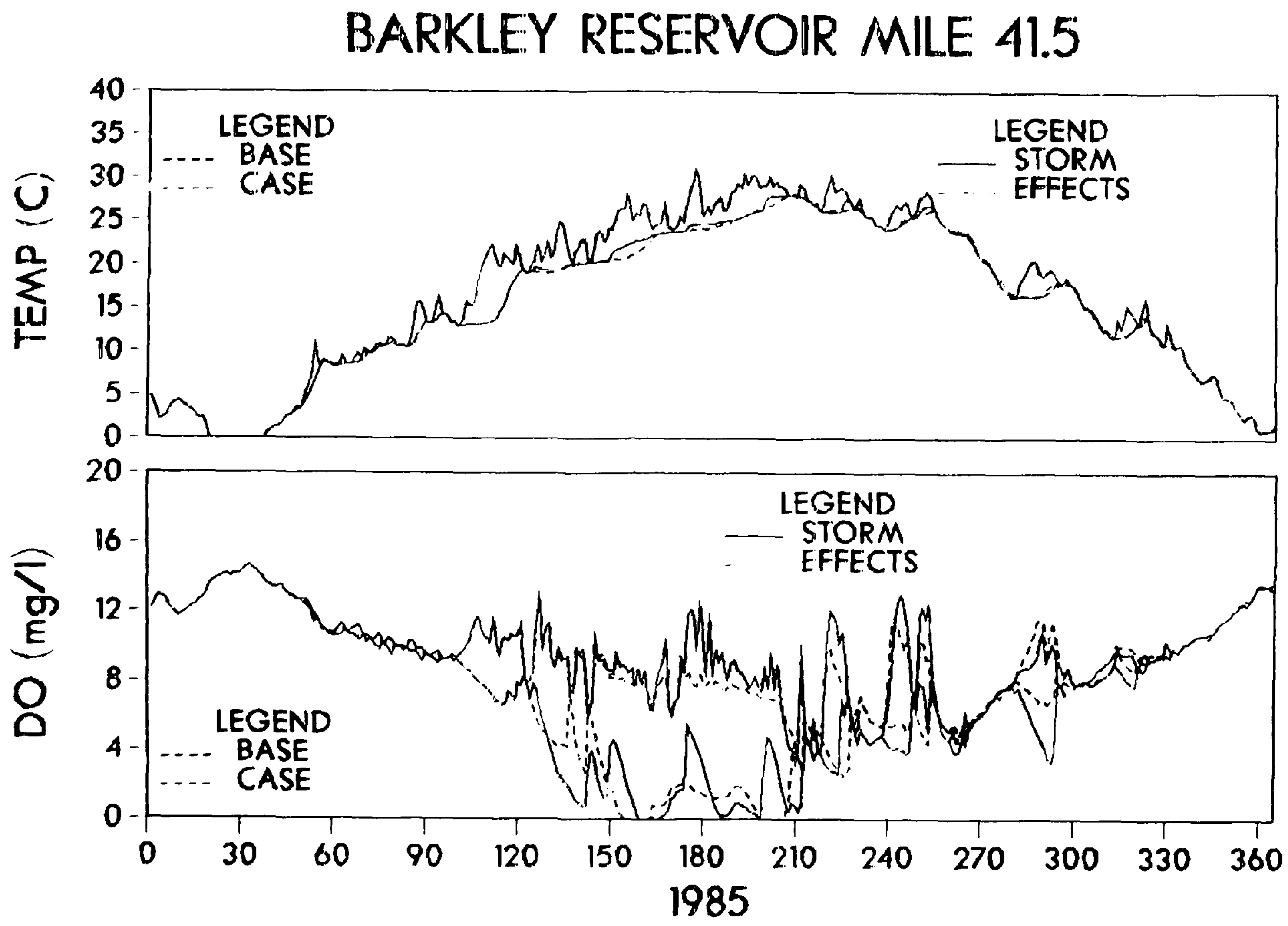


Figure 49 Simulated Effects of Storm Inflows at CuRM 41.5

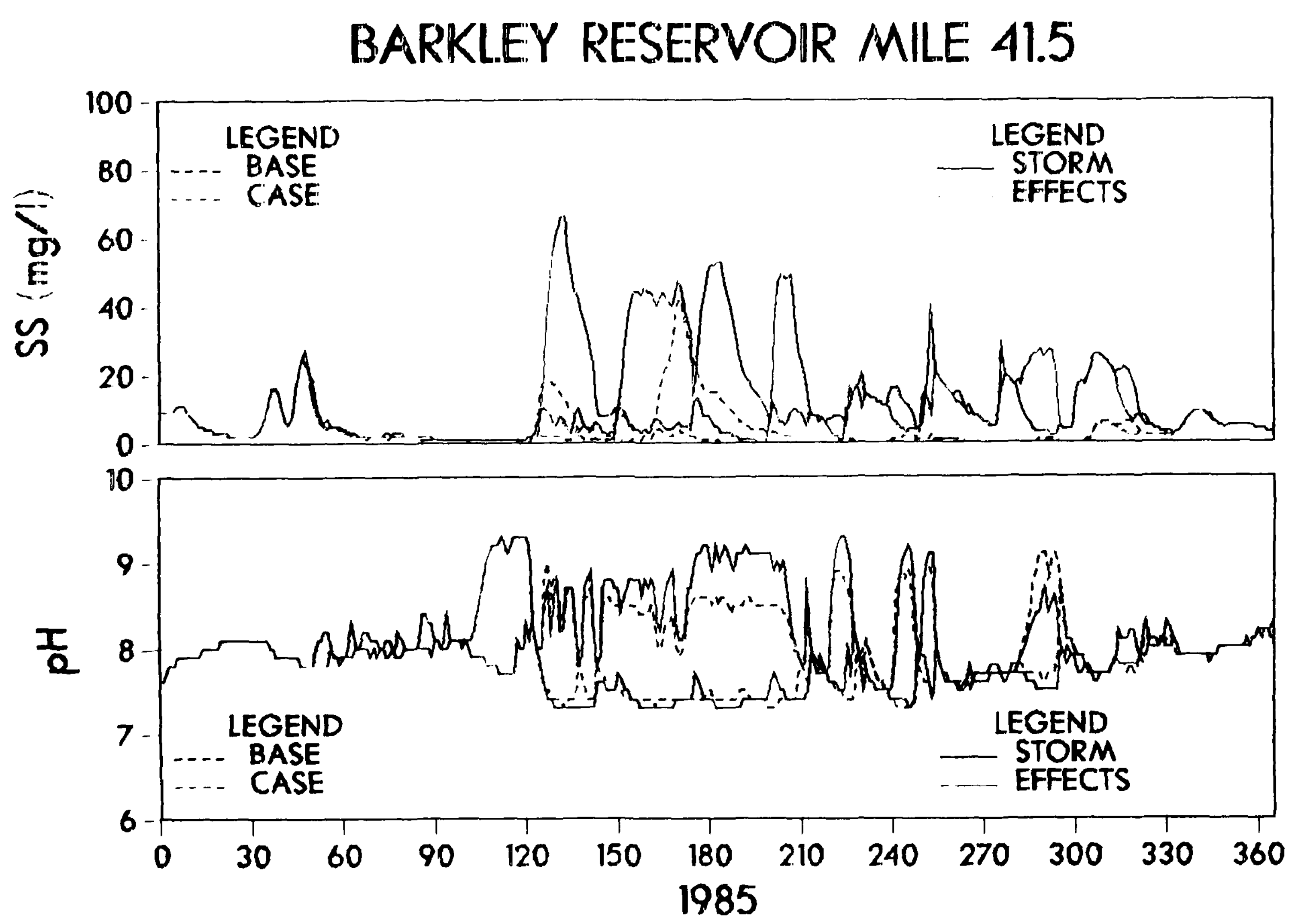


Figure 49 (continued)

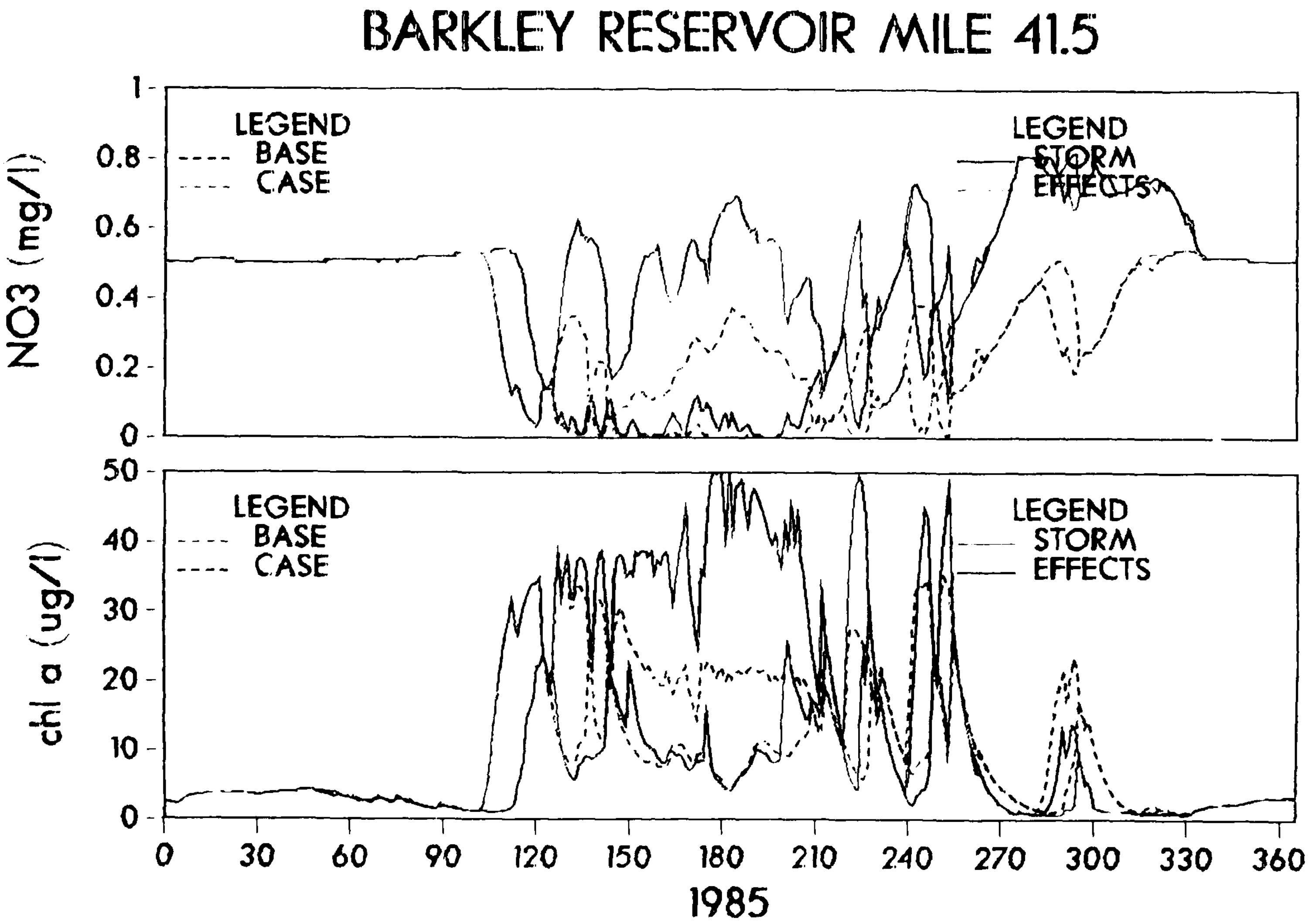


Figure 49 (continued)

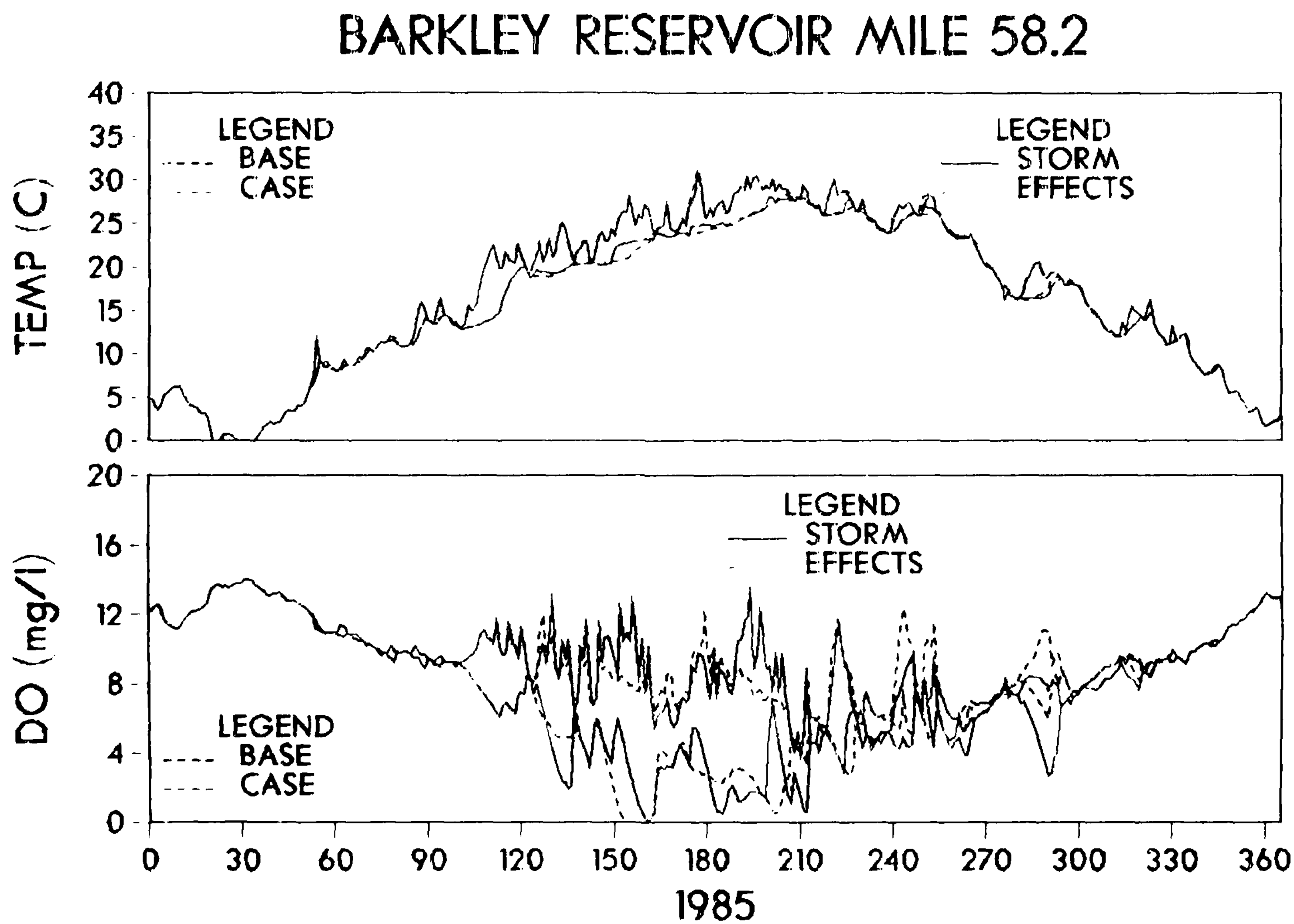


Figure 50 Simulated Effects of Storm Inflows at CuRM 58.2

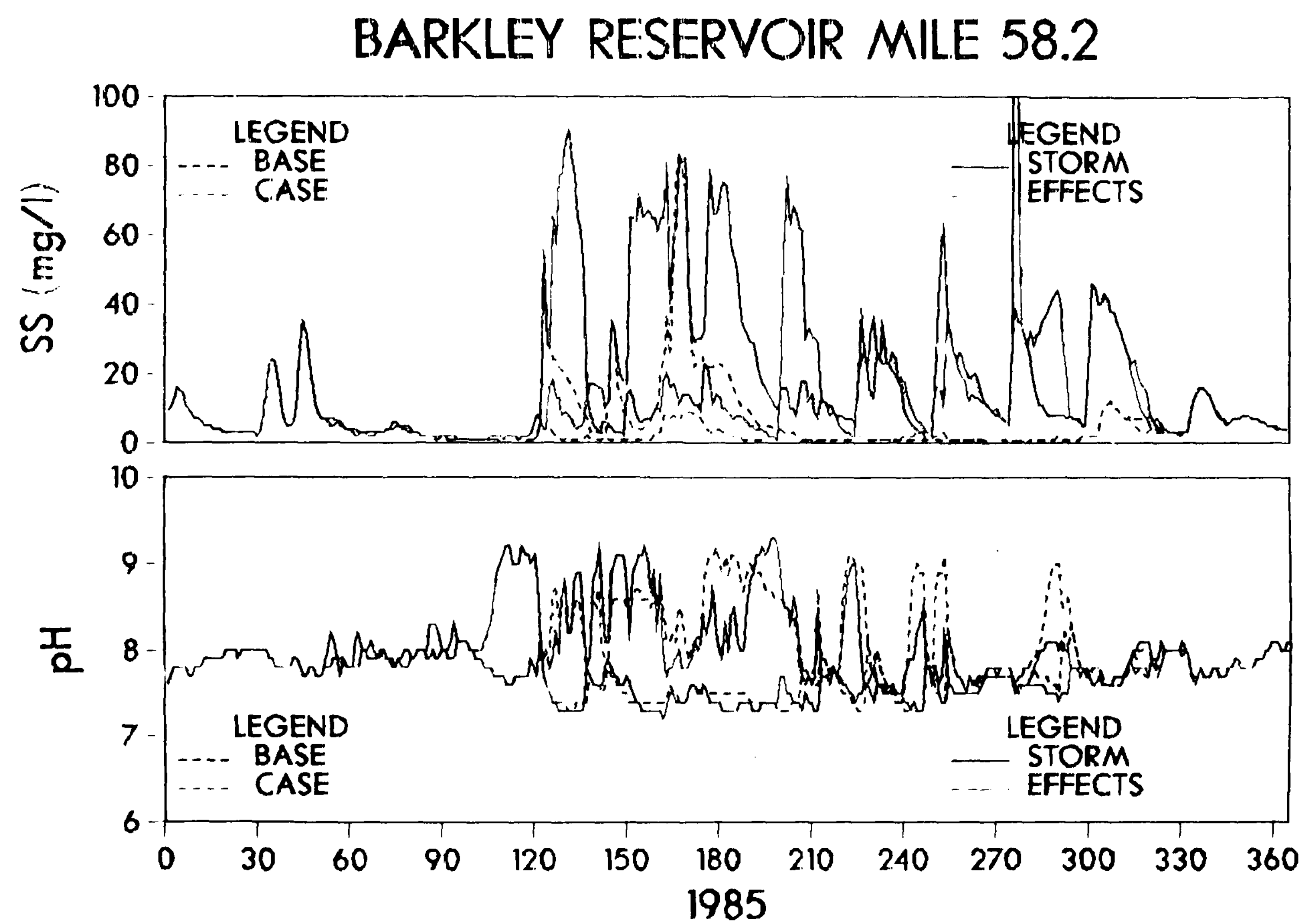
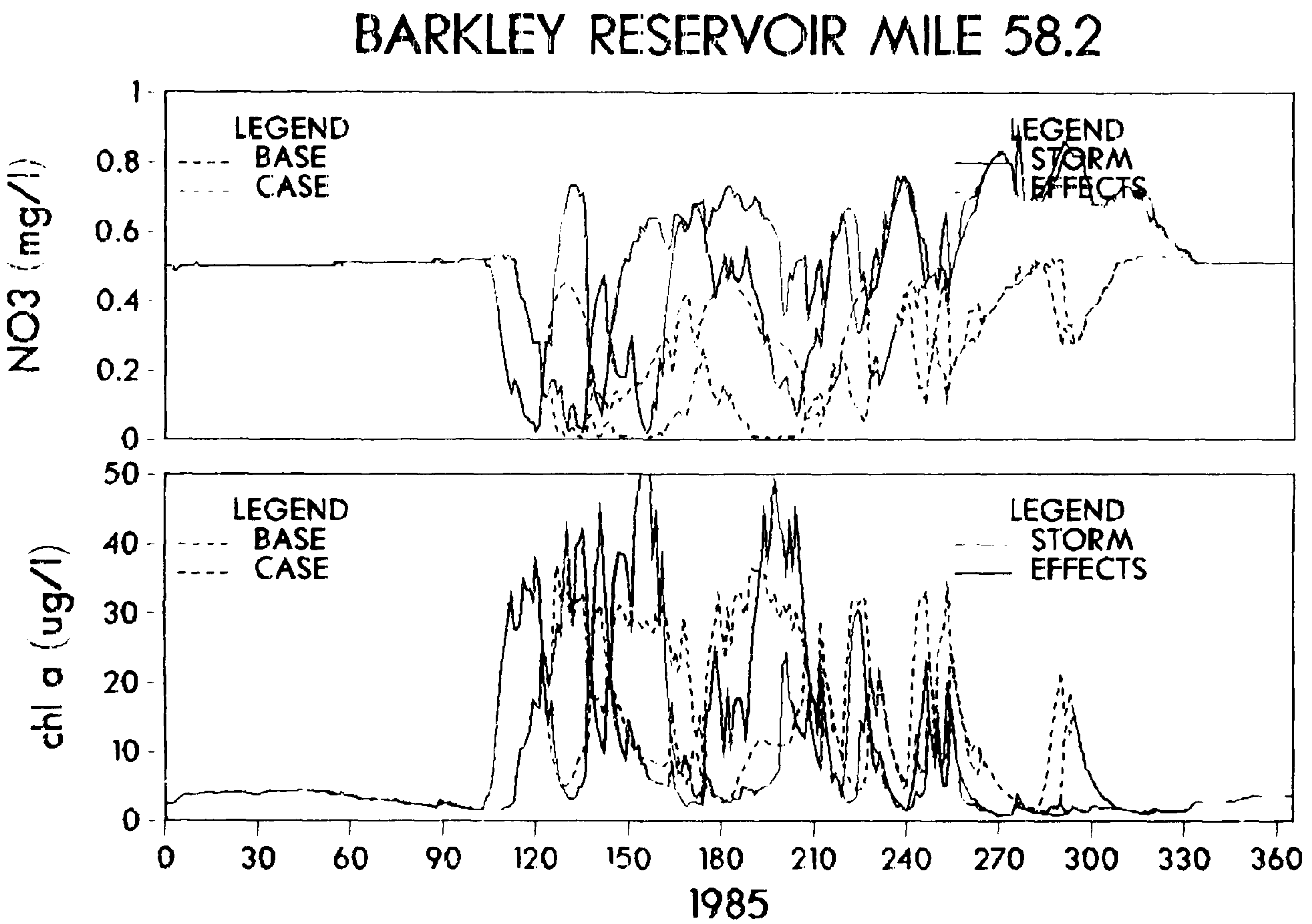


Figure 50 (continued)



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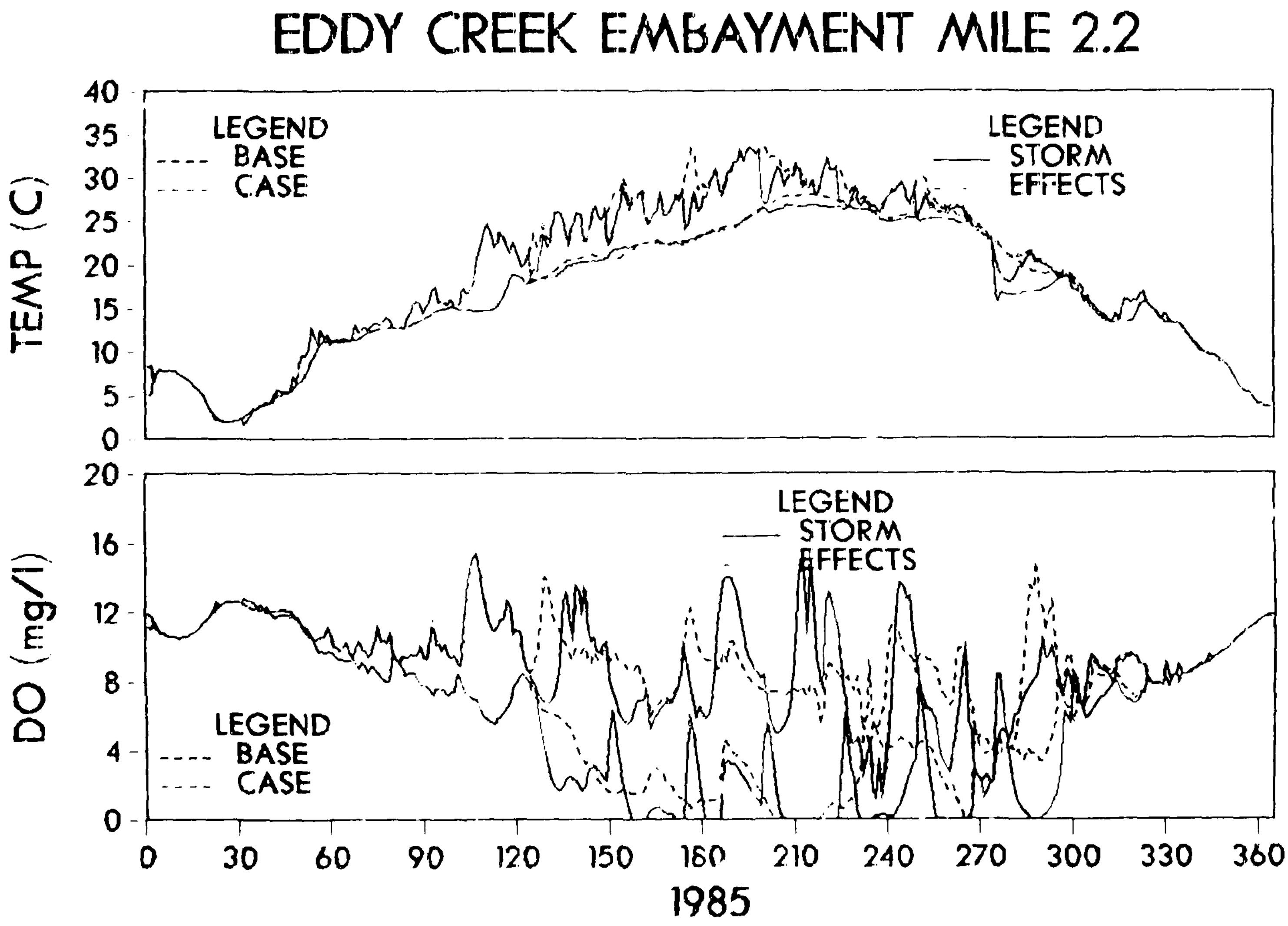


Figure 51 Simulated Effects of Storm Inflows at Eddy Creek Mile 2.2

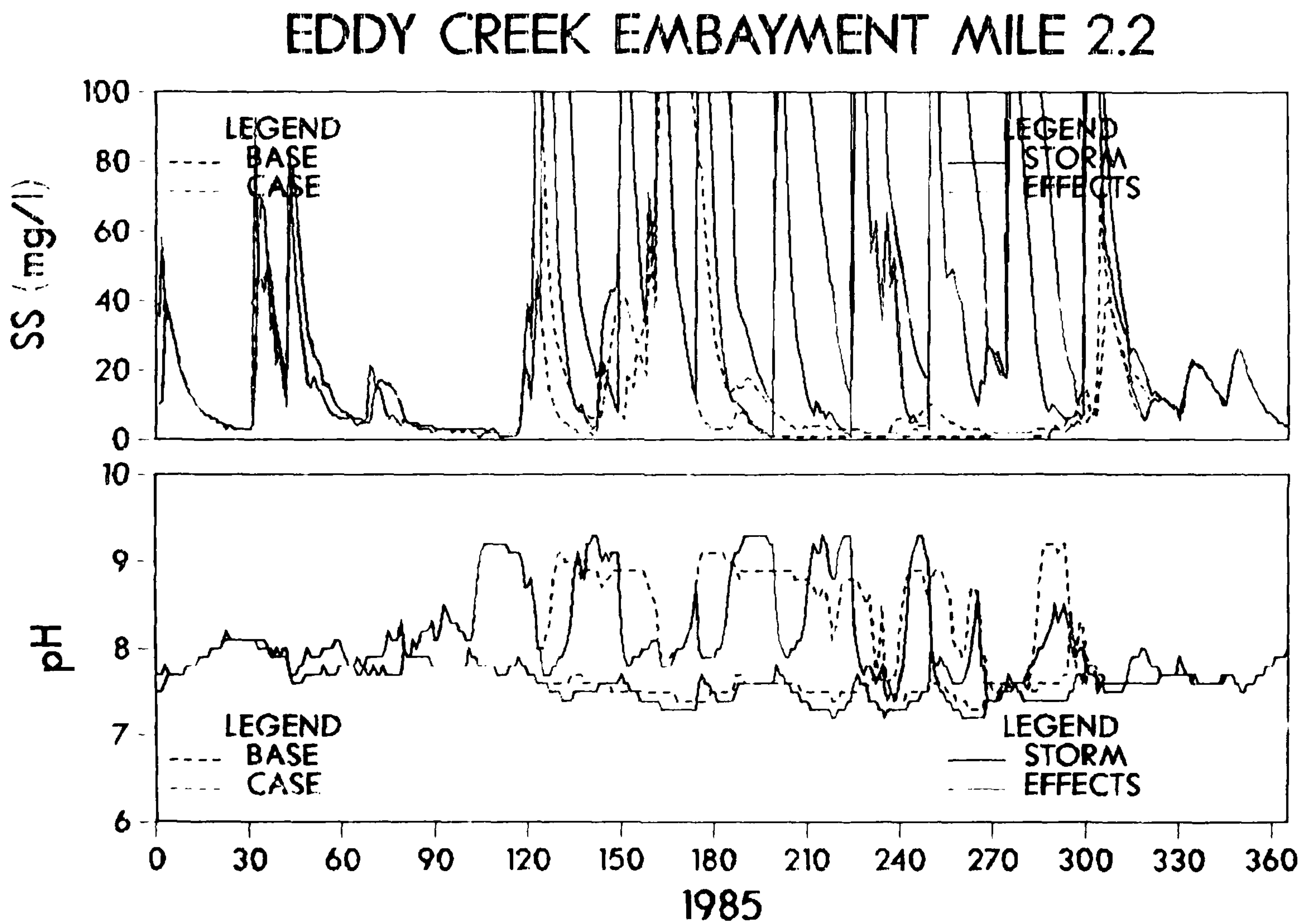


Figure 51 (continued)

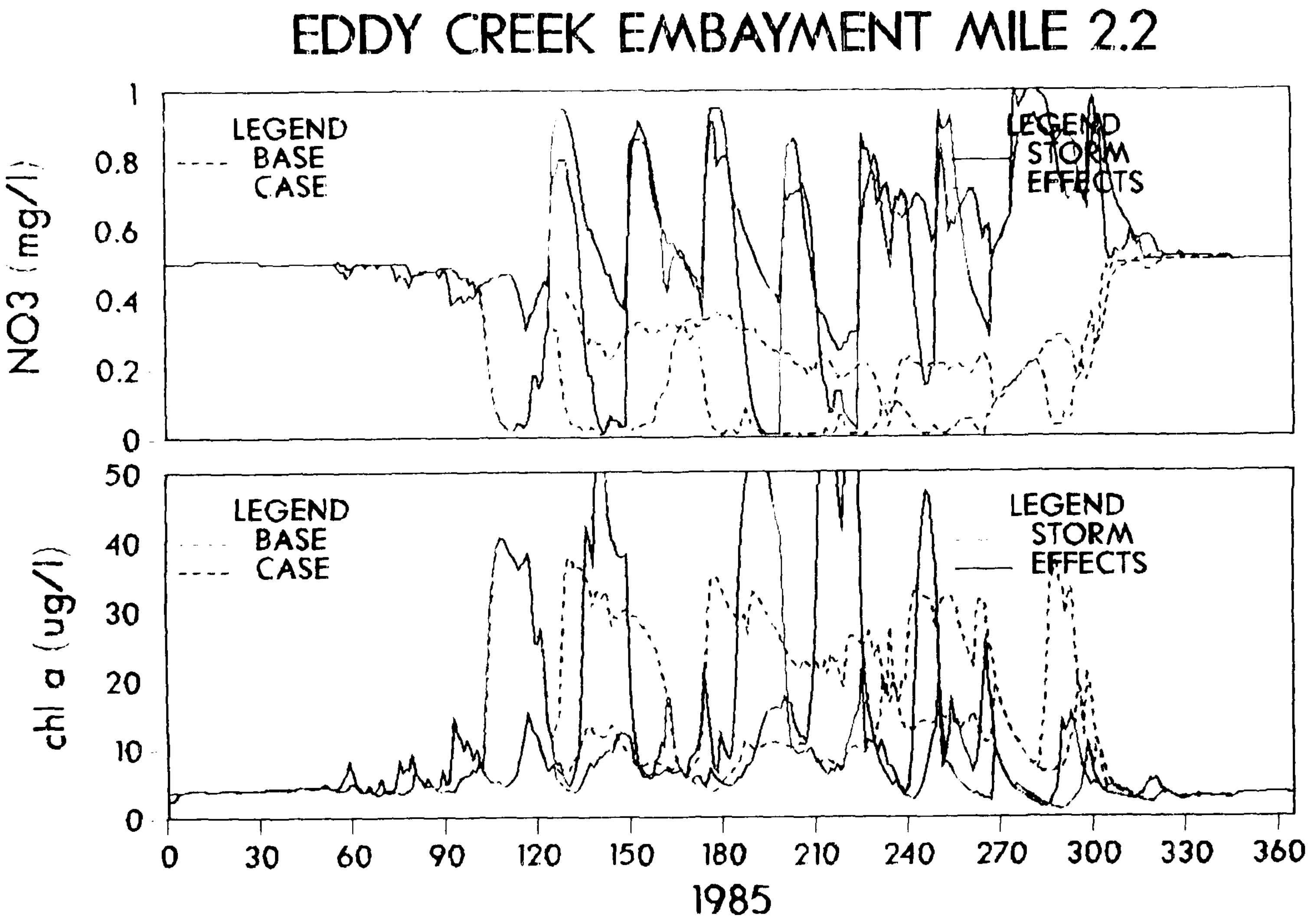


Figure 51 (continued)

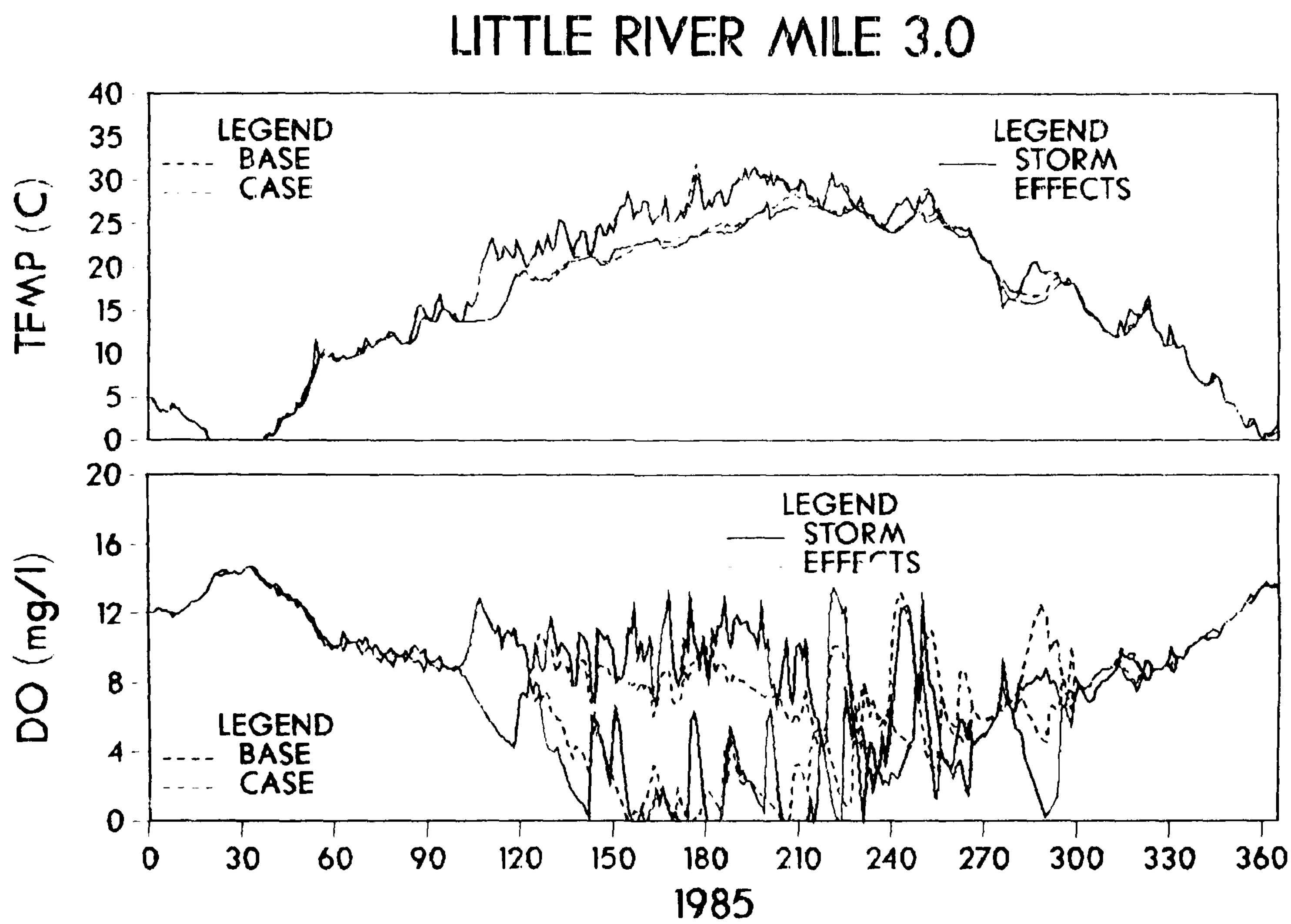
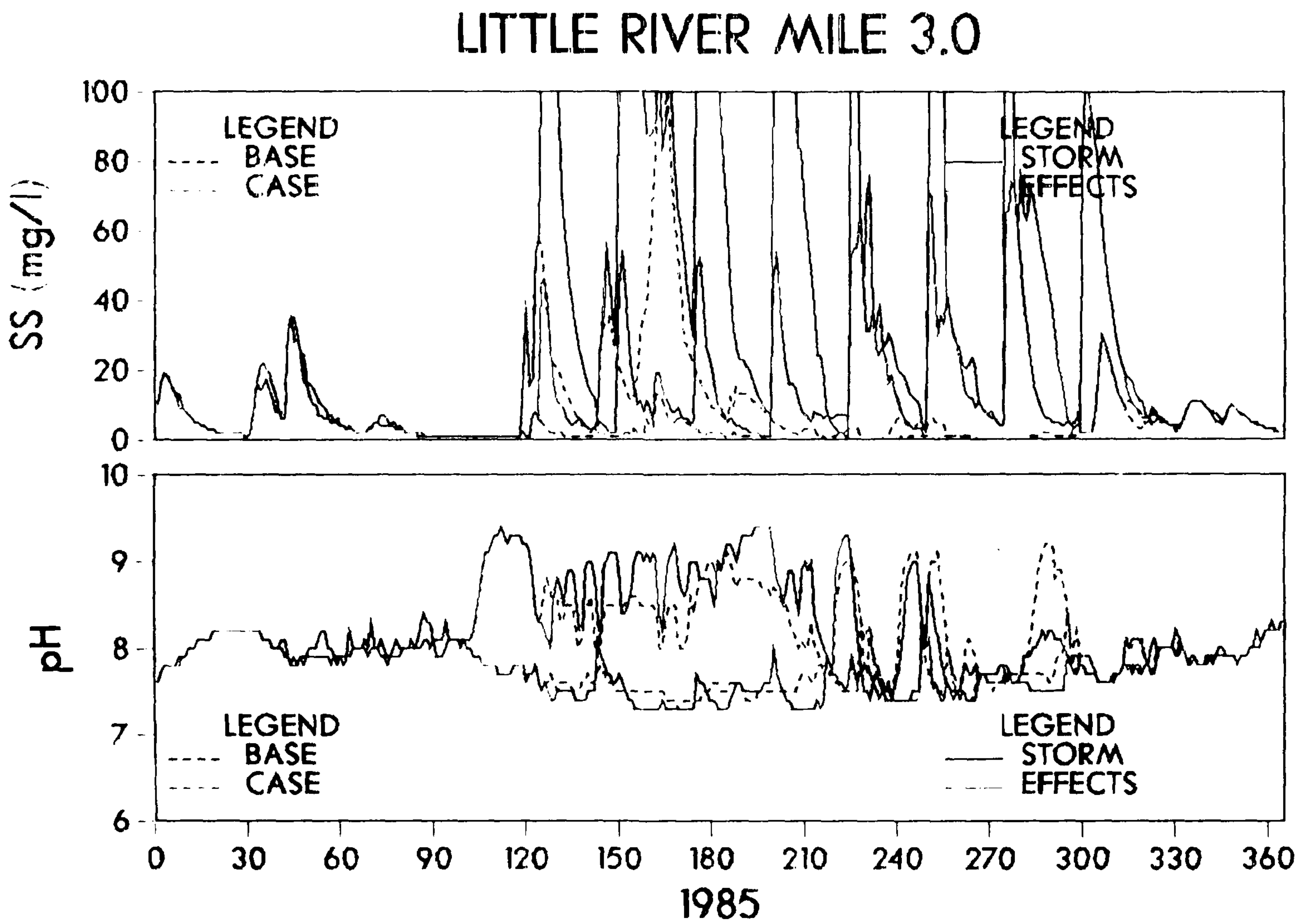


Figure 52 Simulated Effects of Storm Inflows at Little River Mile 3.0



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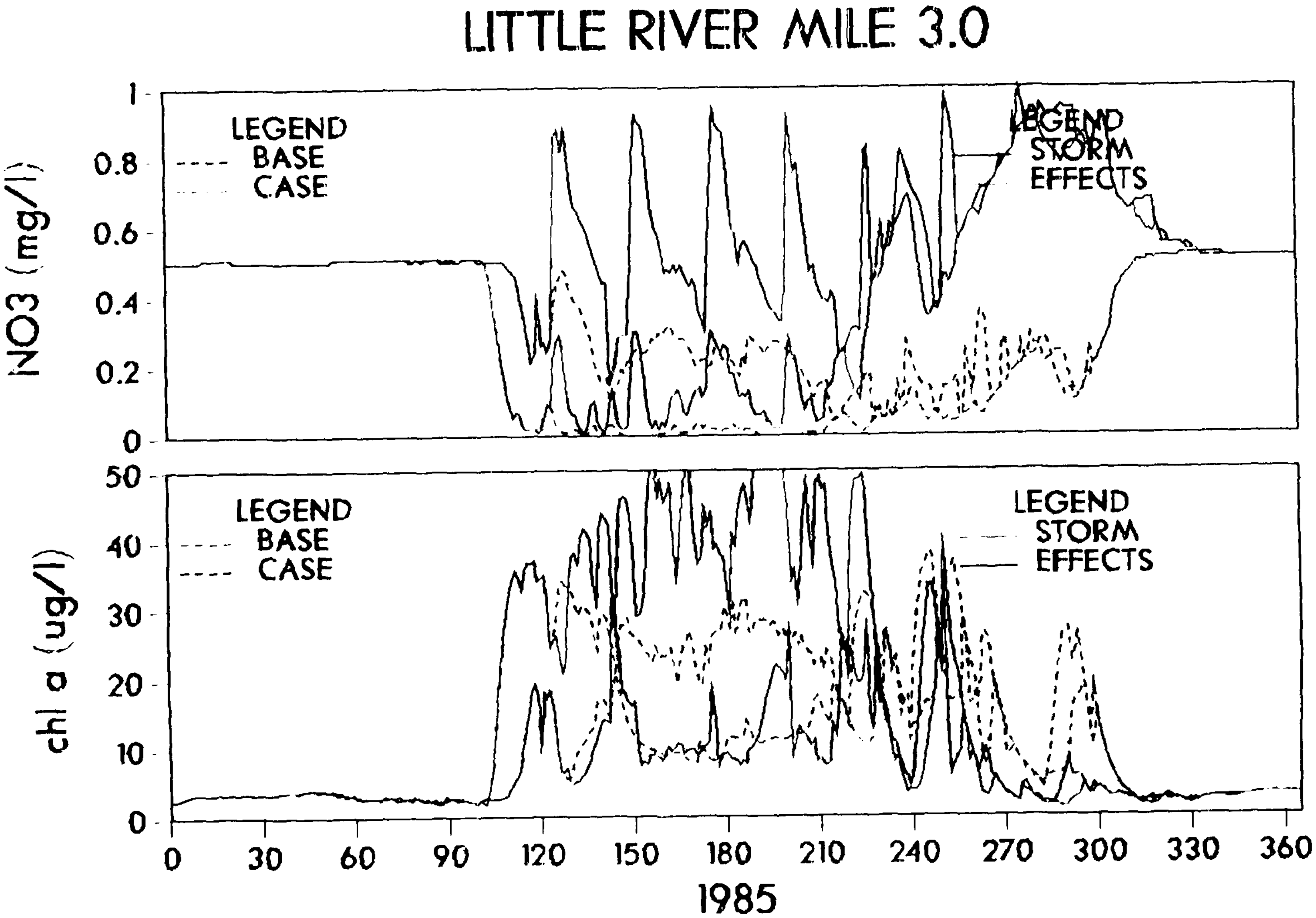


Figure 52 (continued)

Temperatures were slightly affected, depending on the inflow temperatures during the storm days; actual storm inflows may have slightly lower temperatures. The DO patterns were affected by the combination of increased organic loads and increased algal processes. The simulated SS patterns were increased significantly, even downstream at the CuRM 41.5 station. The simulated surface pH were higher, due to the increased nutrients and algal productivity.

The effects in the embayments were quite strong, as expected, since the storm inflow volumes were large relative to the embayment volumes. In the embayments, the organic loading had a strong effect on the DO depletion, and the high SS patterns significantly limited algal activity for several days following the storm inflows. The 25 day interval between storms allowed conditions to return almost to base case values at most stations, indicating that an individual storm will influence lake conditions for perhaps a month following the storm inflow. Since these were relatively large storm flows, with arbitrary high nutrient and organic concentrations, these results are extreme. More realistic simulations of storm effects can be made when storm inflow measurements are made on the major tributaries.

Effects of Cumberland Steam Plant Operations

The effects of the Cumberland Steam Plant operations were simulated by setting the cooling water and thermal discharge flows to zero. The temperature patterns were not affected at the downstream stations. Although a significant amount of heat is discharged from the steam plant, surface heat exchange and mixing is effective in dissipating the heat load without impacting the far field temperature patterns in Lake Barkley. The effects from doubling the heat load, to simulate two power plants, were also relatively minor. Only in the near-field

region, within one of the six-mile long model segments, were there any appreciable impacts from even two steam plants. The major effects from the cooling water flows were caused by the redistribution of flows from the bottom layers into the surface. This had the effect of mixing higher nutrients and SS from the bottom into the surface, and caused more surface water to move into the embayments, producing some minor effects on the simulated chlorophyll patterns. Since these flow patterns cannot be directly confirmed without dye tracer studies, the simulated effects of these cooling water induced circulation patterns should be considered as tentative.

The magnitude of the cooling water flows can be illustrated with surface dye plots, where only the cooling water discharge has been dyed with a value of 100. The results for the base case are shown in Figure 53. Since the steam plant operated nearly continuously during 1985, with a cooling water flow of between 3000 and 4000 cfs, higher dye concentrations are simulated when the surface flow past the steam plant decreases. During the stratified period, the cooling water contributed approximately 30% of the surface water in the main channel downstream of the steam plant. The results indicate that cooling water moves into the Little River embayment at the surface, contributing about 20% of the surface water in the first three mile segment. The results for the increased cooling water flow are shown in Figure 54 The increased cooling water flow increased the surface water contribution in the downstream segments to about 50% and increased the surface inflow into the embayments. Dyed water was transported ten miles up the Little River embayment according to the simulation results. But the direct effects from these thermal discharges on lake temperatures were minor.

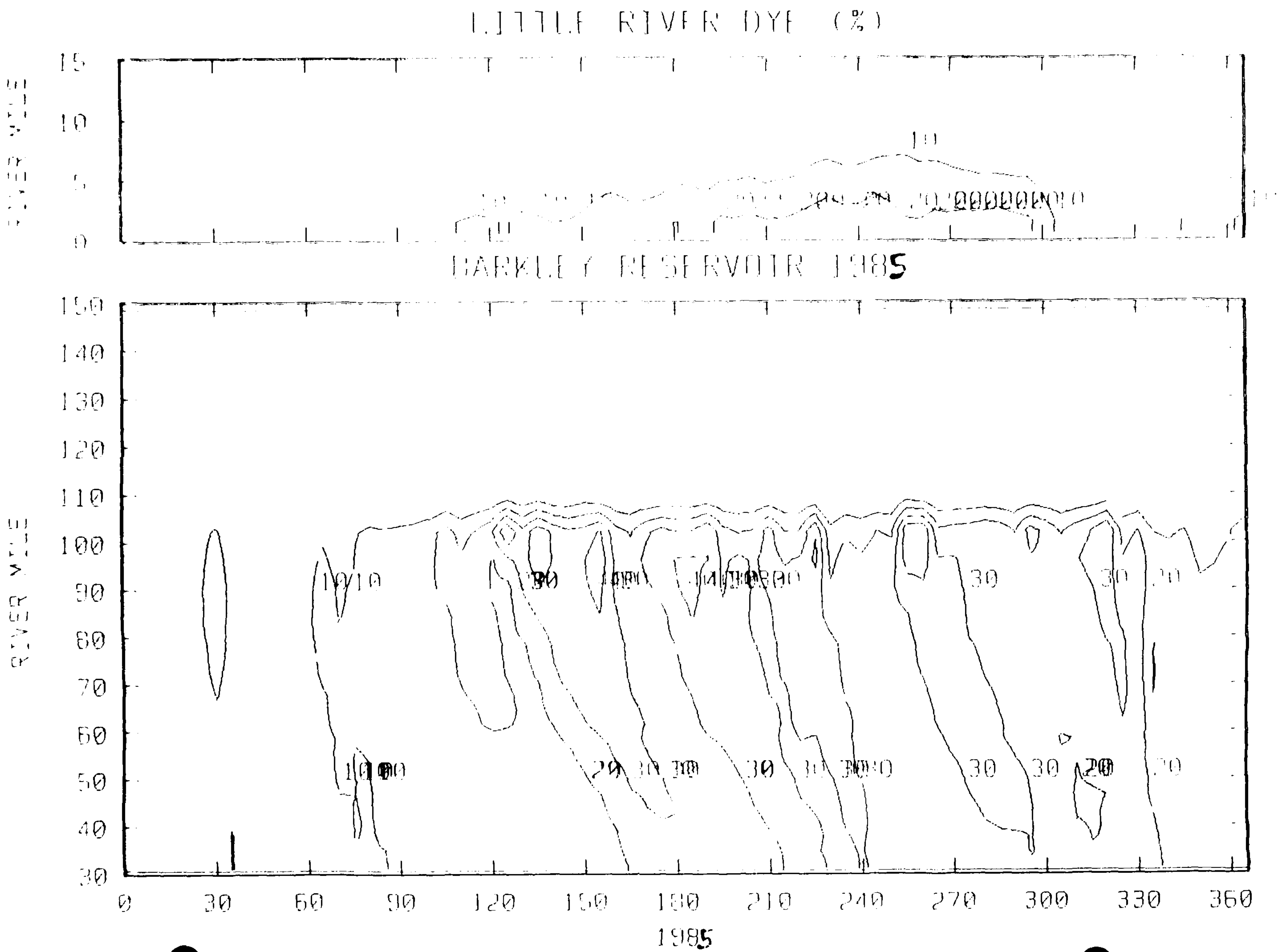


Figure 3 Modeled Surface Dye Patterns from Cumberland Steam Plant Dischar[illegible] for 1985

DOUBLE STEAM PLANT

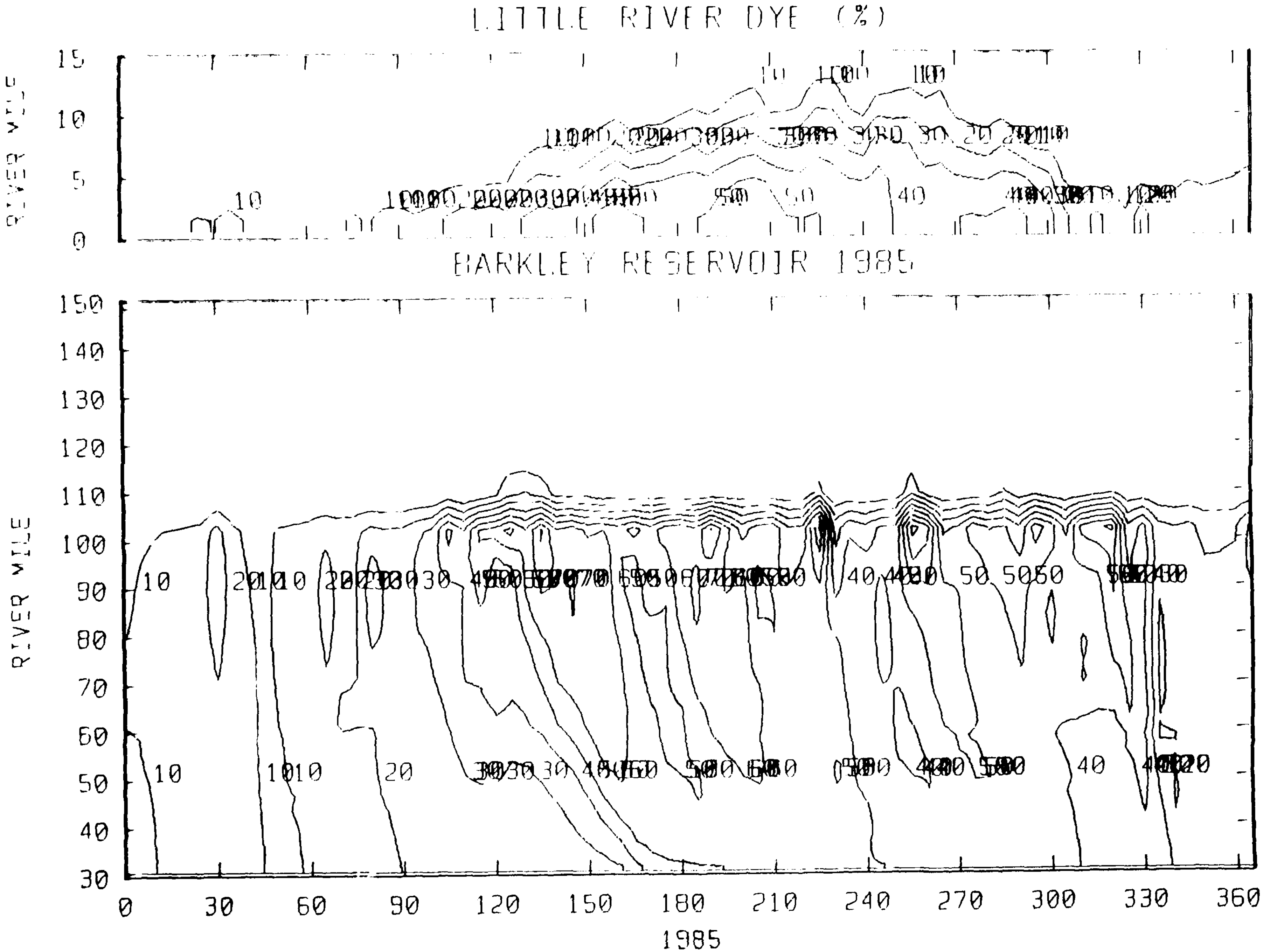


Figure 54 Modeled Surface Dye Patterns from 2X Cumberland Steam Plant Discharges for 1985

Effects from Mixing Processes

The vertical gradients in water quality were found to be very sensitive to stratification and mixing processes during the calibration. This sensitivity was further demonstrated by increasing and decreasing the turbulent and wind mixing coefficients. The turbulent mixing coefficient, DC, was increased from 1.0 to 2.0; and the windspeed factor was increased from 0.9 to 1.5. Since wind mixing energy is proportional to windspeed cubed, this increased the wind mixing by a factor of 4.5, and doubled the vertical mixing from advective turbulence. The results are shown in Figures 55 to 58. All water quality variables were affected by the increased magnitude of the mixing mechanisms. Temperatures were reduced from increased evaporation, and stratification was greatly reduced, with only occasional stratification episodes in the main channel. Only the Eddy Creek embayment stations remained stratified for extended periods, suggesting that the balance between heating and mixing was somewhat different in this relatively small, downstream embayment. DO depletion was greatly reduced in all of the segments, since stratified periods were much shorter. The vertical mixing kept the SS values mixed and the maximum bottom SS values following turbid storm inflows were reduced. The vertical pH gradients were reduced, with the bottom values raised closer to 8.0. Nutrient uptake was greatly reduced, since periods of ideal algal growth were decreased by vertical mixing that limited available light. The simulated chlorophyll values were correspondingly reduced. The mixing effects were strongest at CuRM 58.2, where nearly continuous vertical mixing eliminated DO depletion and algal activity. The effects were weakest in Eddy Creek embayment, which remained somewhat more stratified than the other stations.

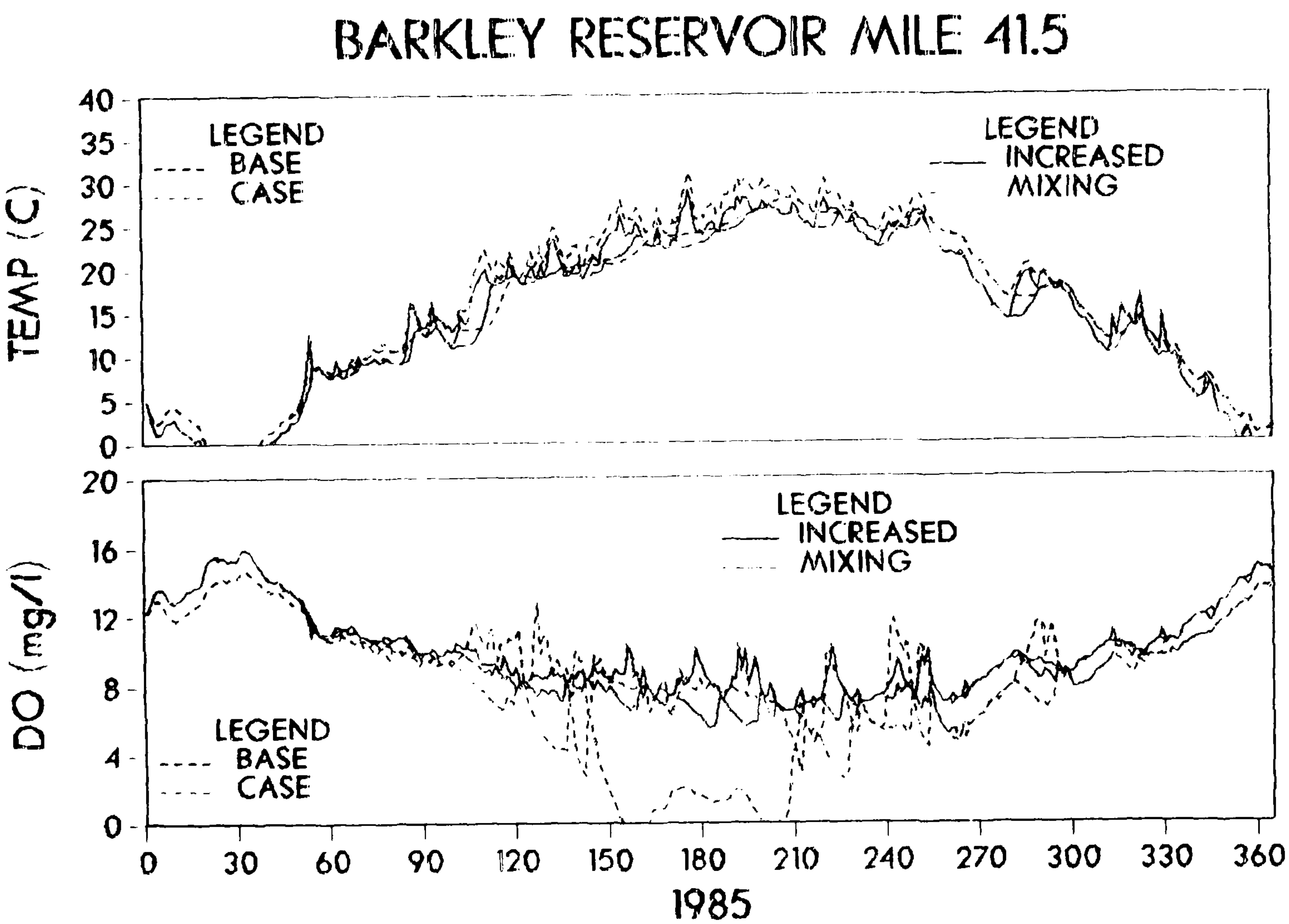


Figure 55 Simulated Effects of Increased Mixing at CuRM 41.5

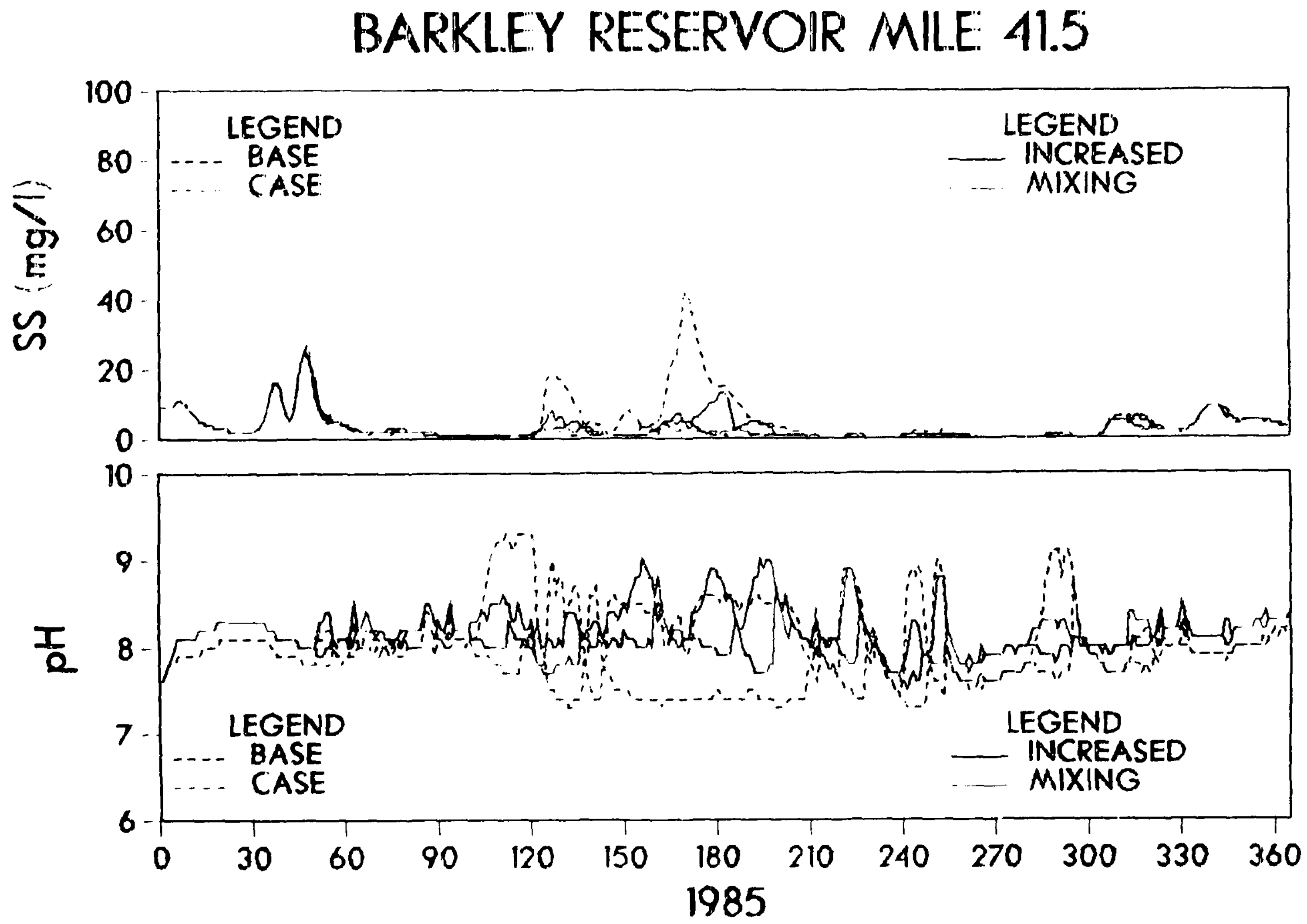
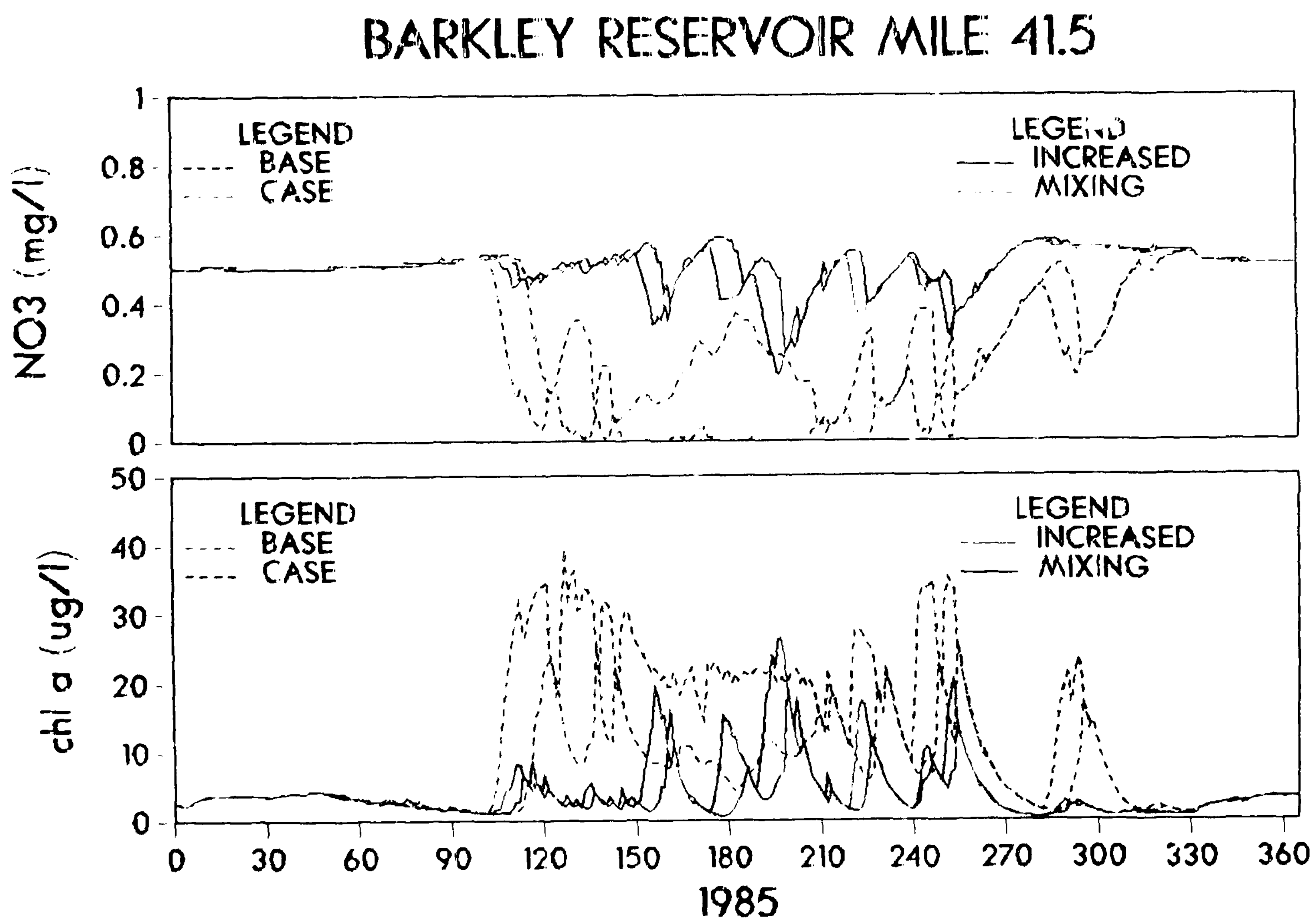


Figure 55 (continued)



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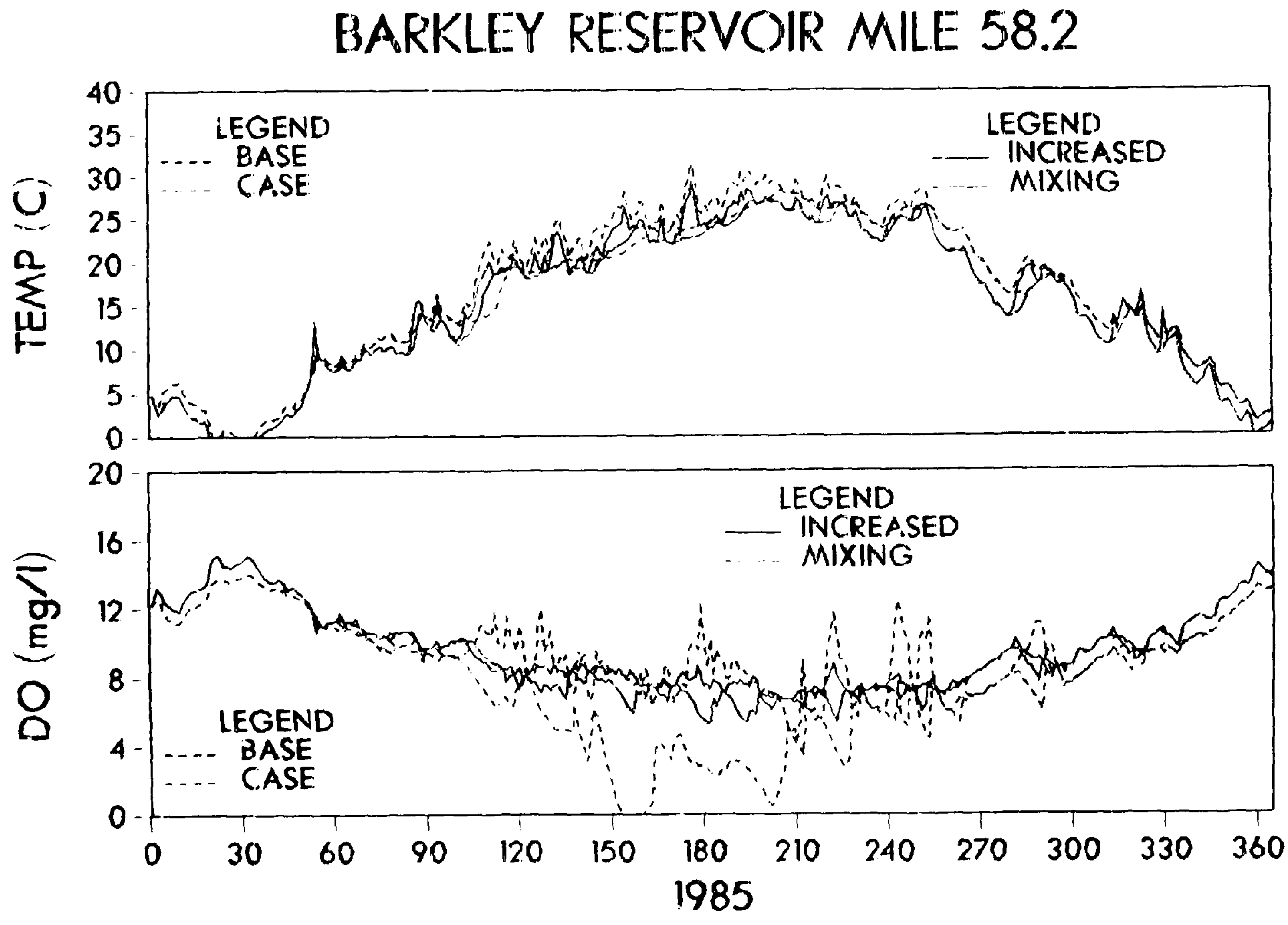


Figure 56 Simulated Effects of Increased Mixing at CuRM 58.2

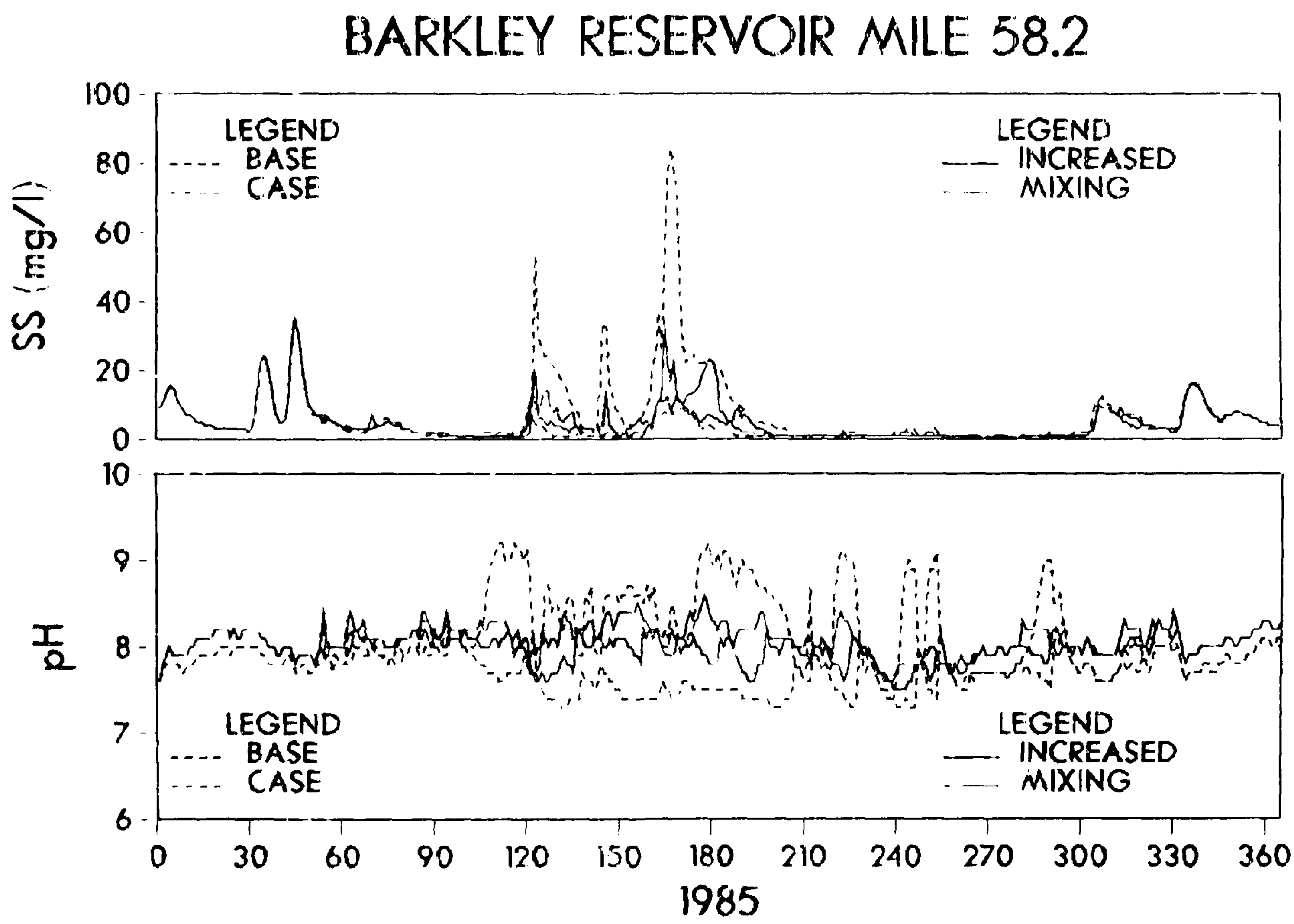
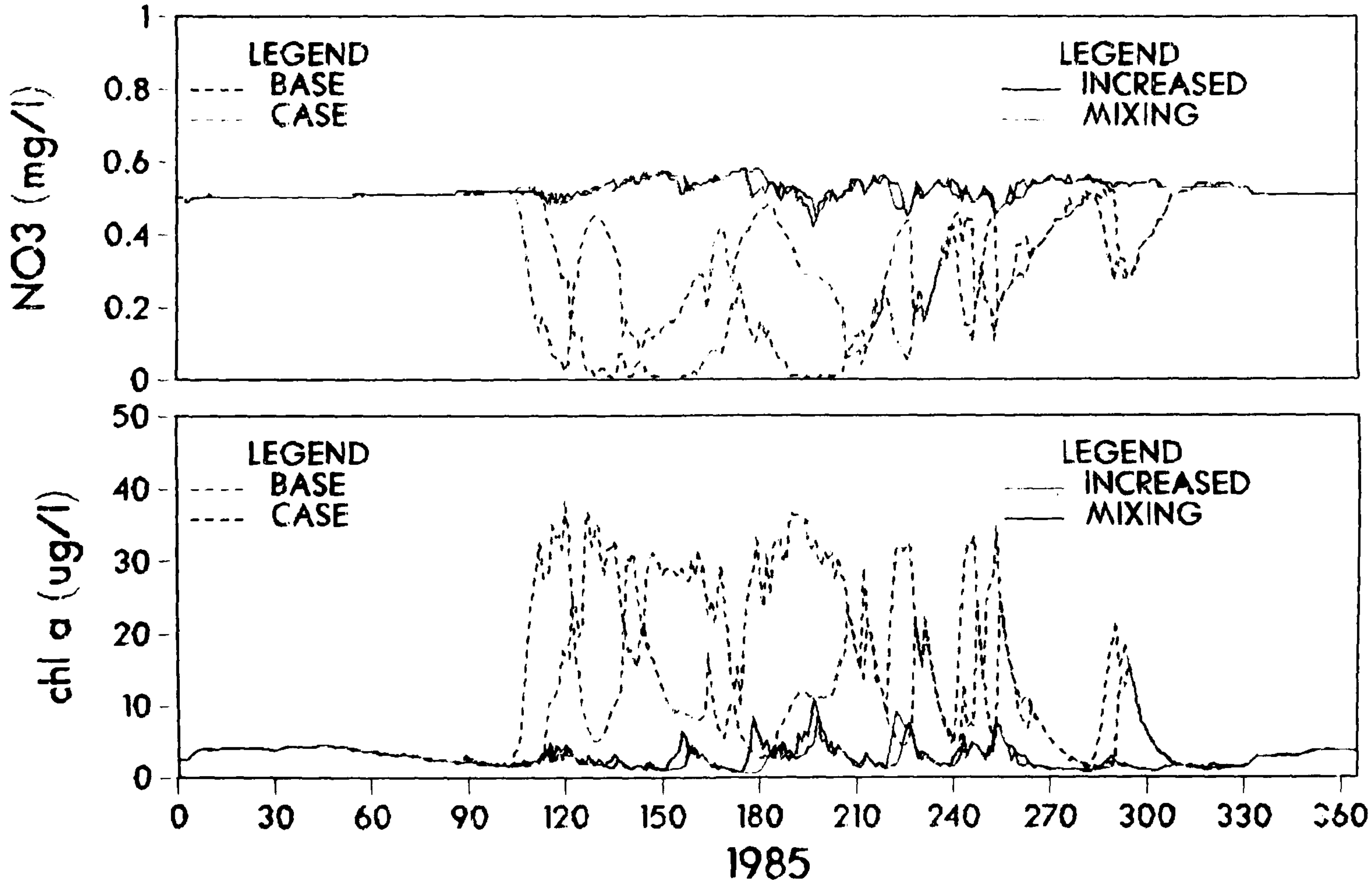


Figure 56 (continued)

BARKLEY RESERVOIR MILE 58.2



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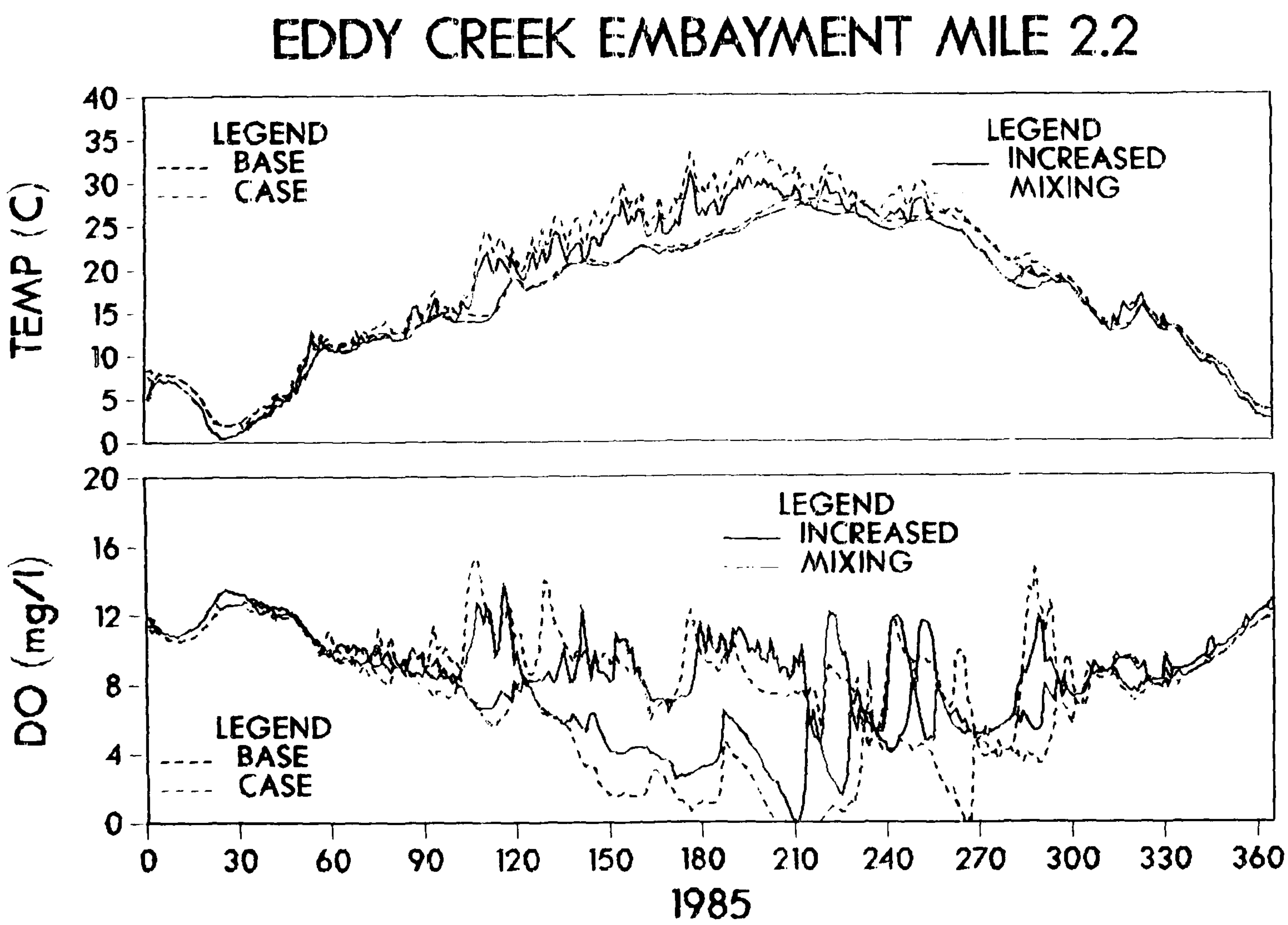


Figure 57 Simulated Effects of Increased Mixing at Eddy Creek Mile 2.2

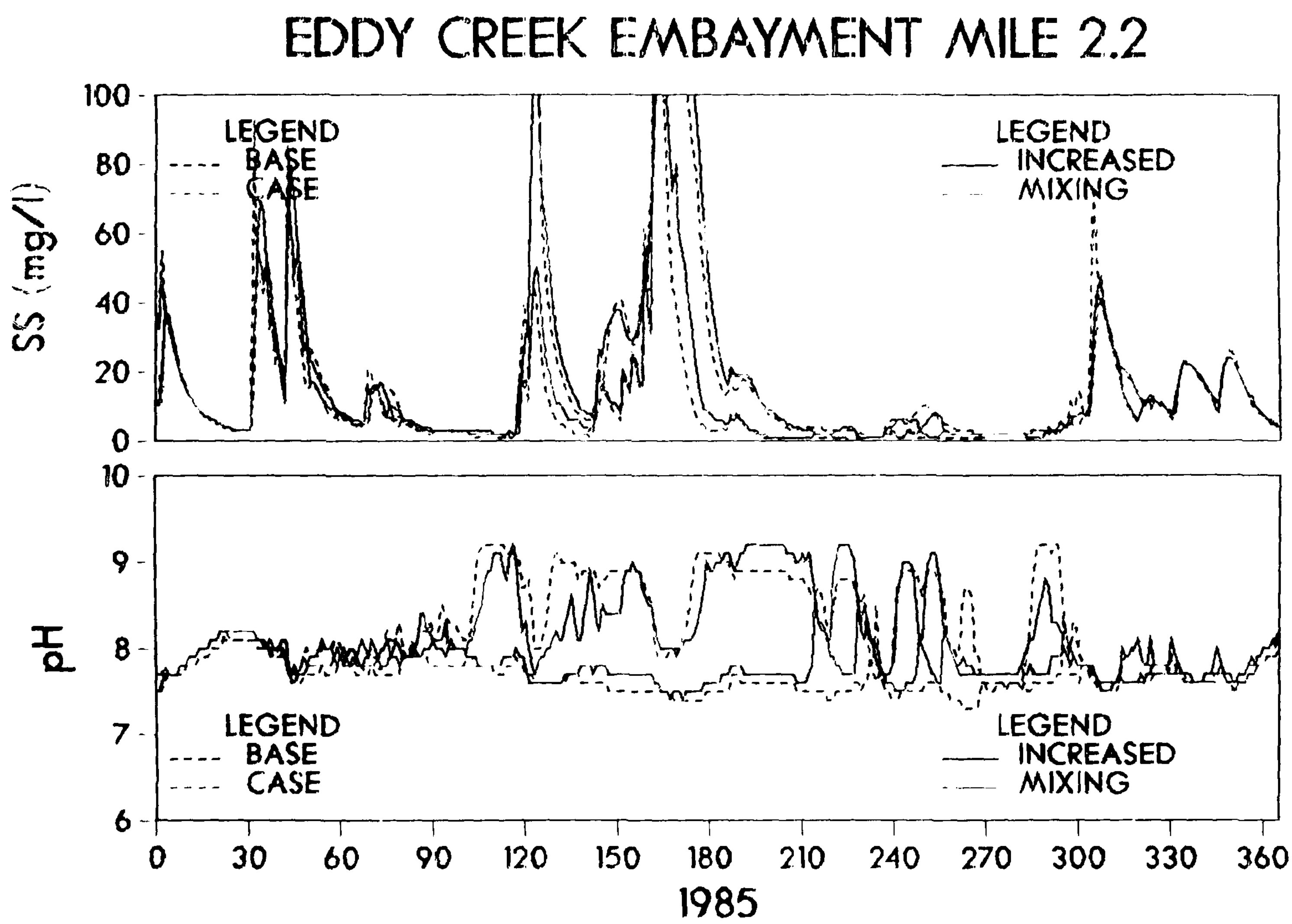


Figure 57 (continued)

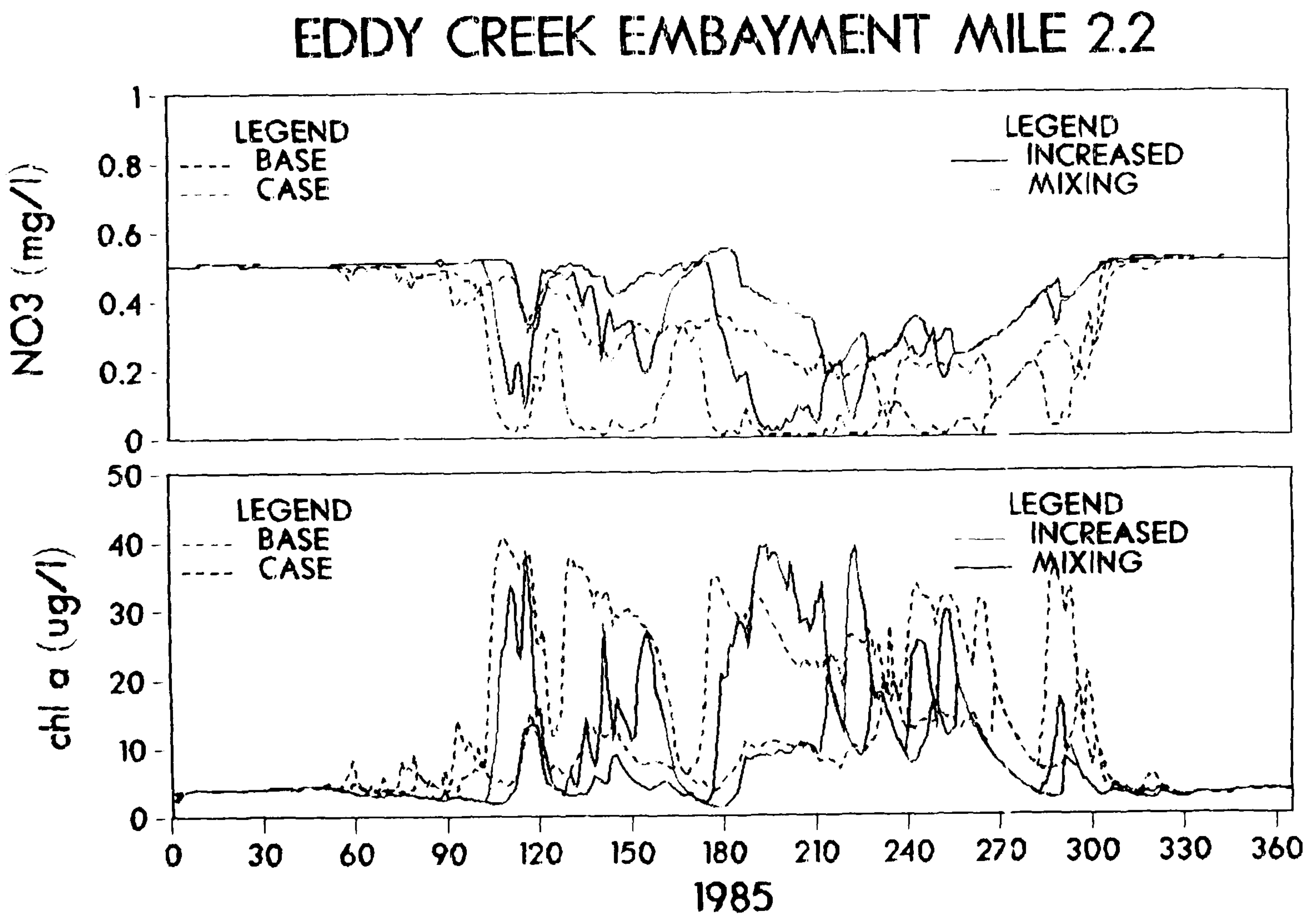


Figure 57 (continued)

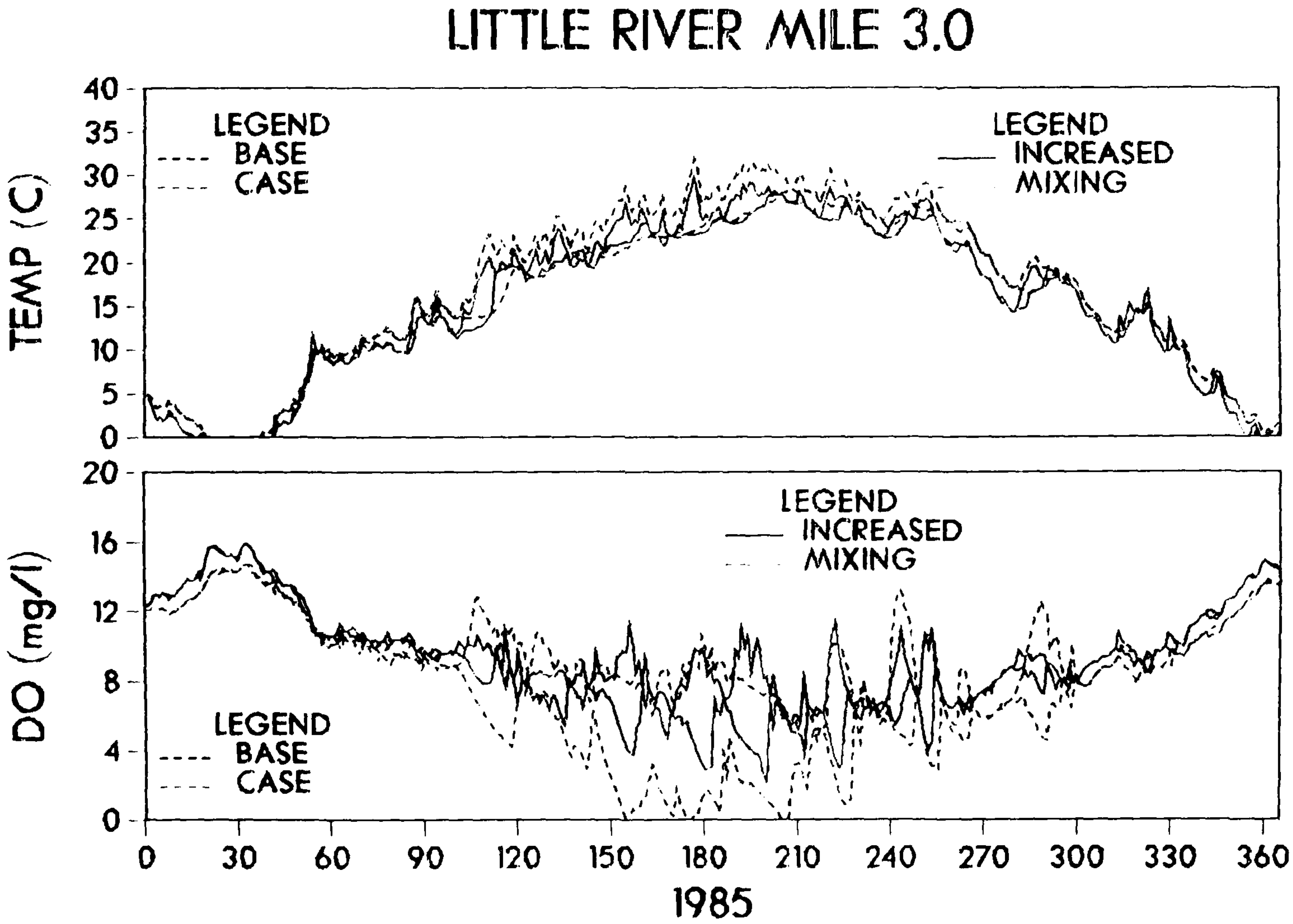


Figure 58 Simulated Effects of Increased Mixing at Little River Mile 3.0

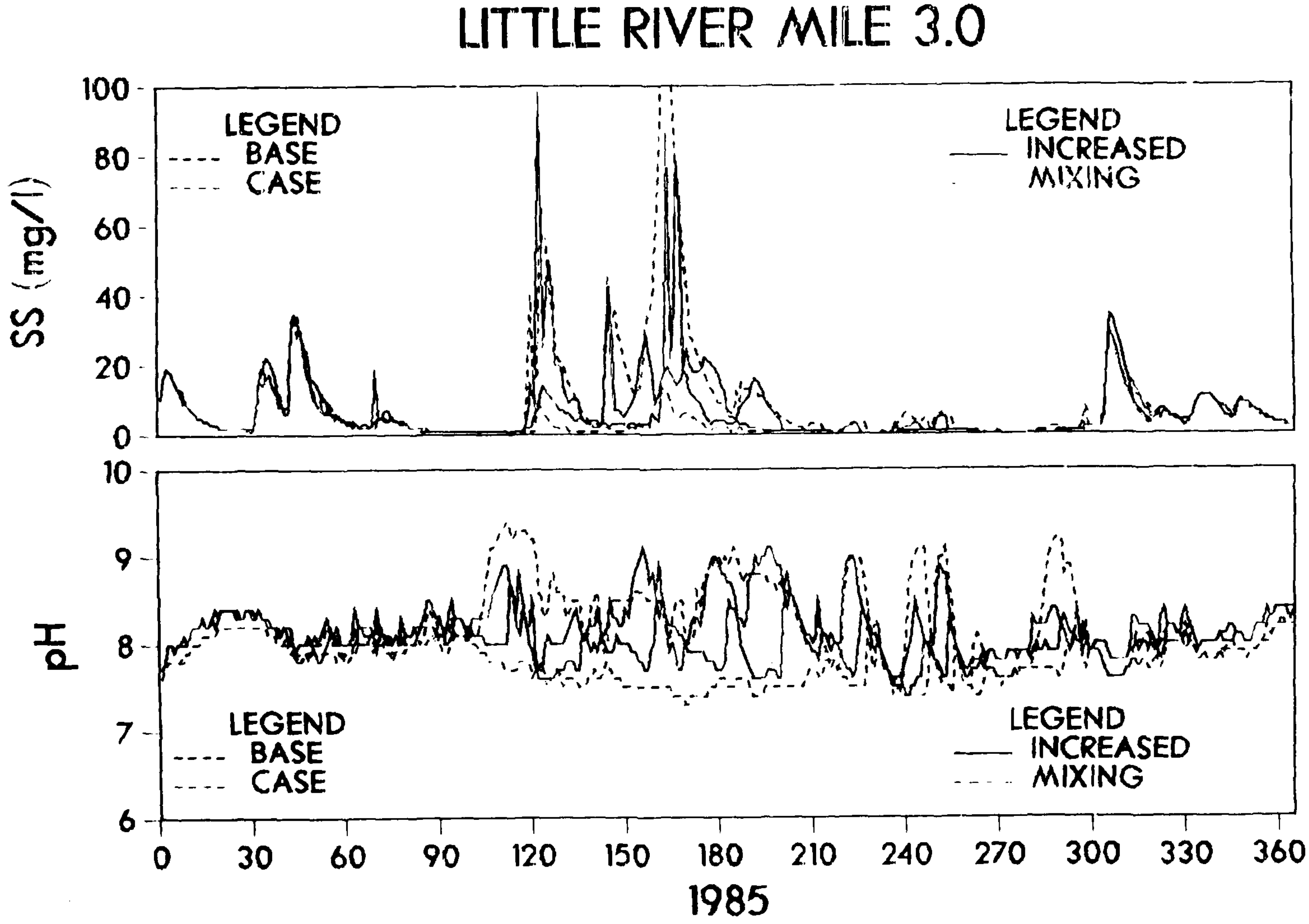


Figure 58 (continued)

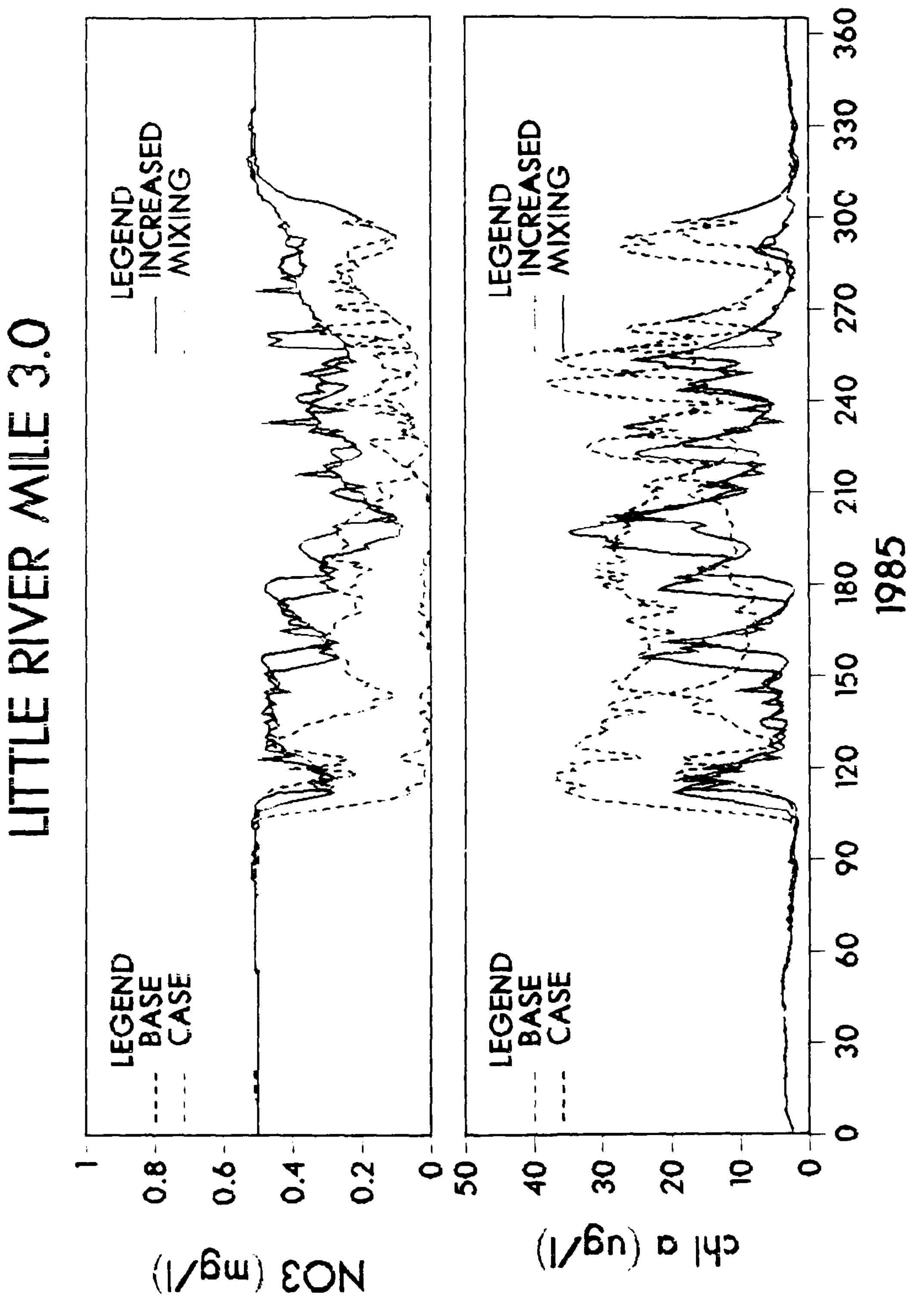


Figure 58 (continued)

The mixing coefficients were then reduced: DC was set at 0.5, and the windspeed factor, WDFAC, was set at 0.5, which reduced the wind mixing to just 17% of the base case. The results are shown in Figures 59 to 62. The stratification and vertical water quality gradients were increased, although intermittent mixing episodes from surface cooling events were still simulated. Simulated surface temperatures were higher from reduced evaporation and fewer mixing events. The effects were strongest in the main channel. Stratification began earlier, so DO depletion occurred during the spring as well as the summer. Algal growth occurred earlier and began farther upstream, so that the nutrients at CuRM 58.2 and CuRM 41.5 were depleted earlier, causing a reduction in simulated chlorophyll during the summer. Effects in the embayments were relatively minor, since these stations were already more strongly stratified. Eddy Creek simulations were almost identical to the base case, but the Little River embayment simulations were affected by the reduced mixing much the same as the main channel stations. These sensitivity results indicate the importance of mixing processes in determining water quality patterns in Lake Barkley. The different responses simulated at the four stations indicate the range of conditions that exist in the same lake, due to the balance between stratification and mixing processes. Although the calibrated coefficients appear to adequately portray these differences, more detailed field data will be required to verify the actual mixing regimes in these portions of Barkley Lake.

Effects of Sediment Oxygen Demand Rates

The sediment oxygen demand (SOD) rates were adjusted during calibration to provide the observed DO depletion patterns by setting the main channel segment SOD values at 1.0 mg-O_2/m^2-day and the embayment segment SOD values at 1.5

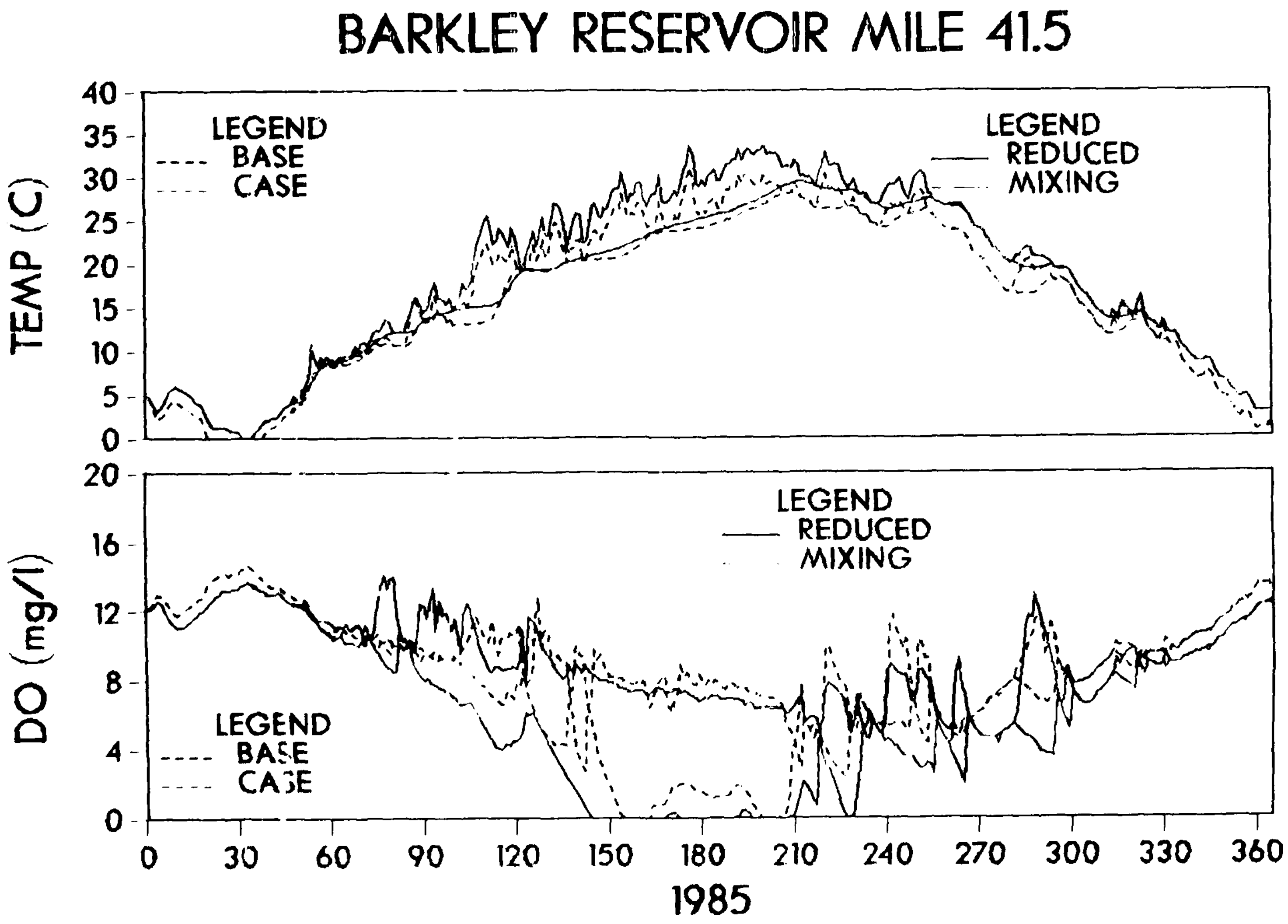
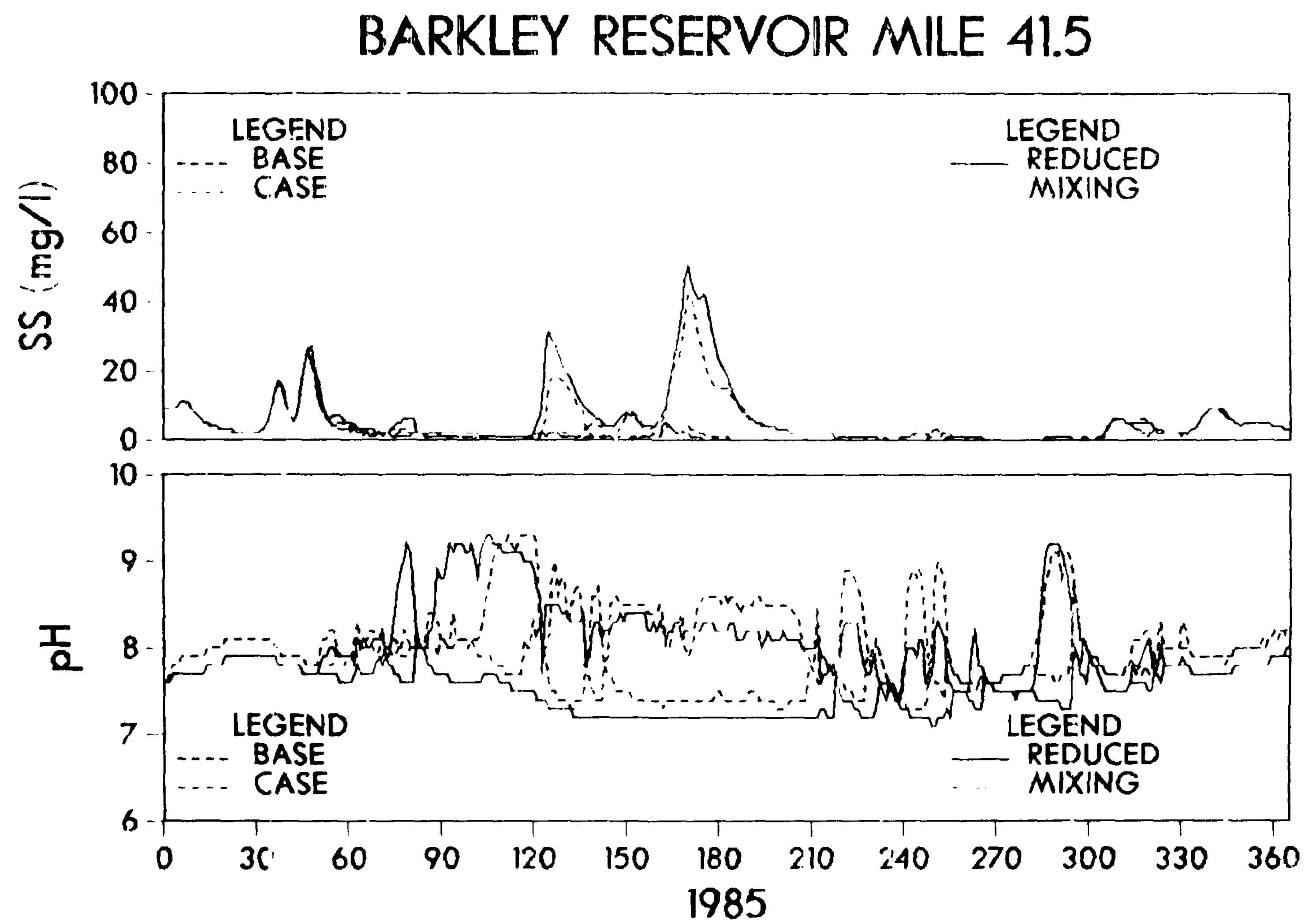


Figure 59 Simulated Effects of Reduced Mixing at CuRM 41.5



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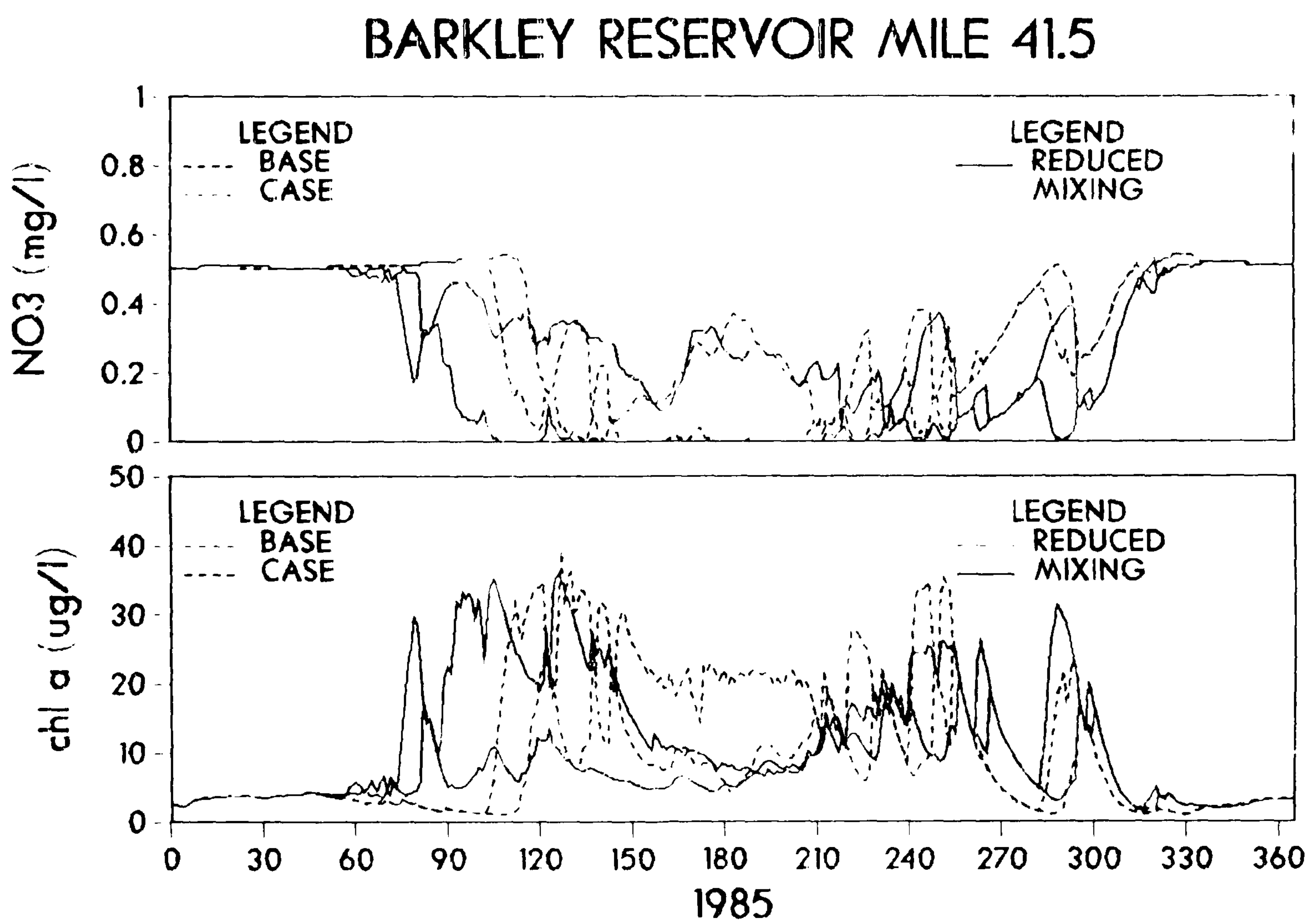

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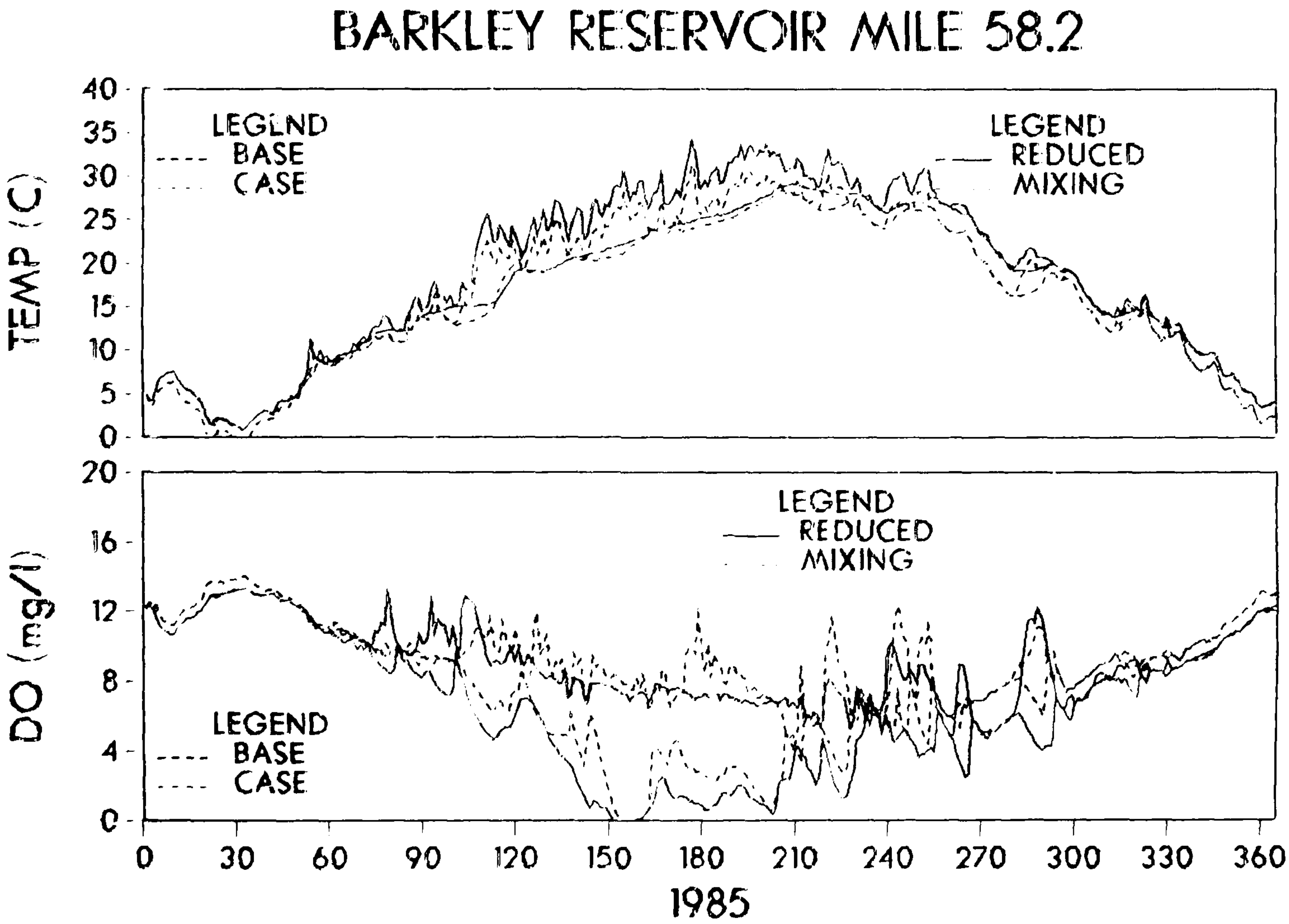
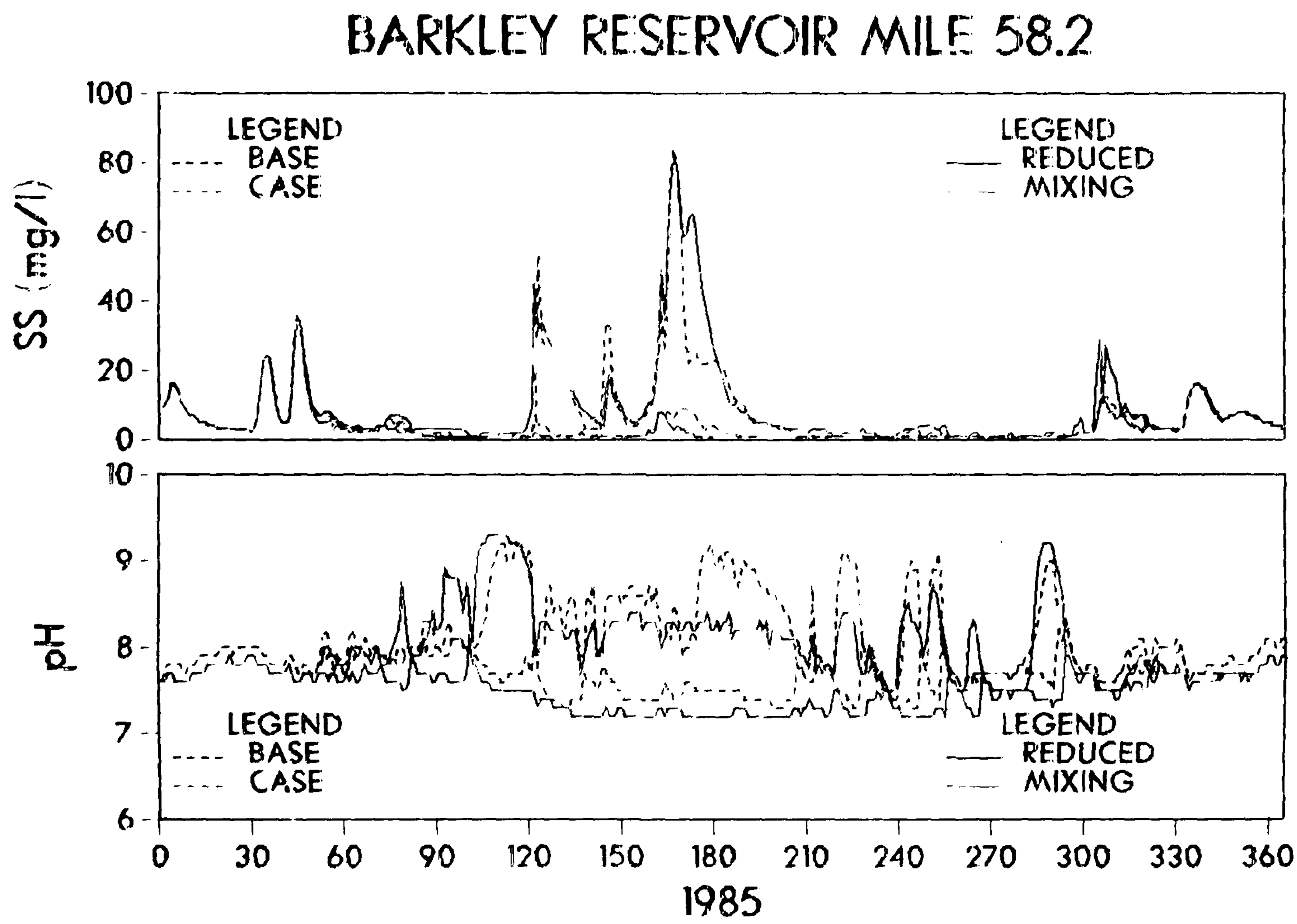


Figure 60 Simulated Effects of Reduced Mixing at CuRM 58.2



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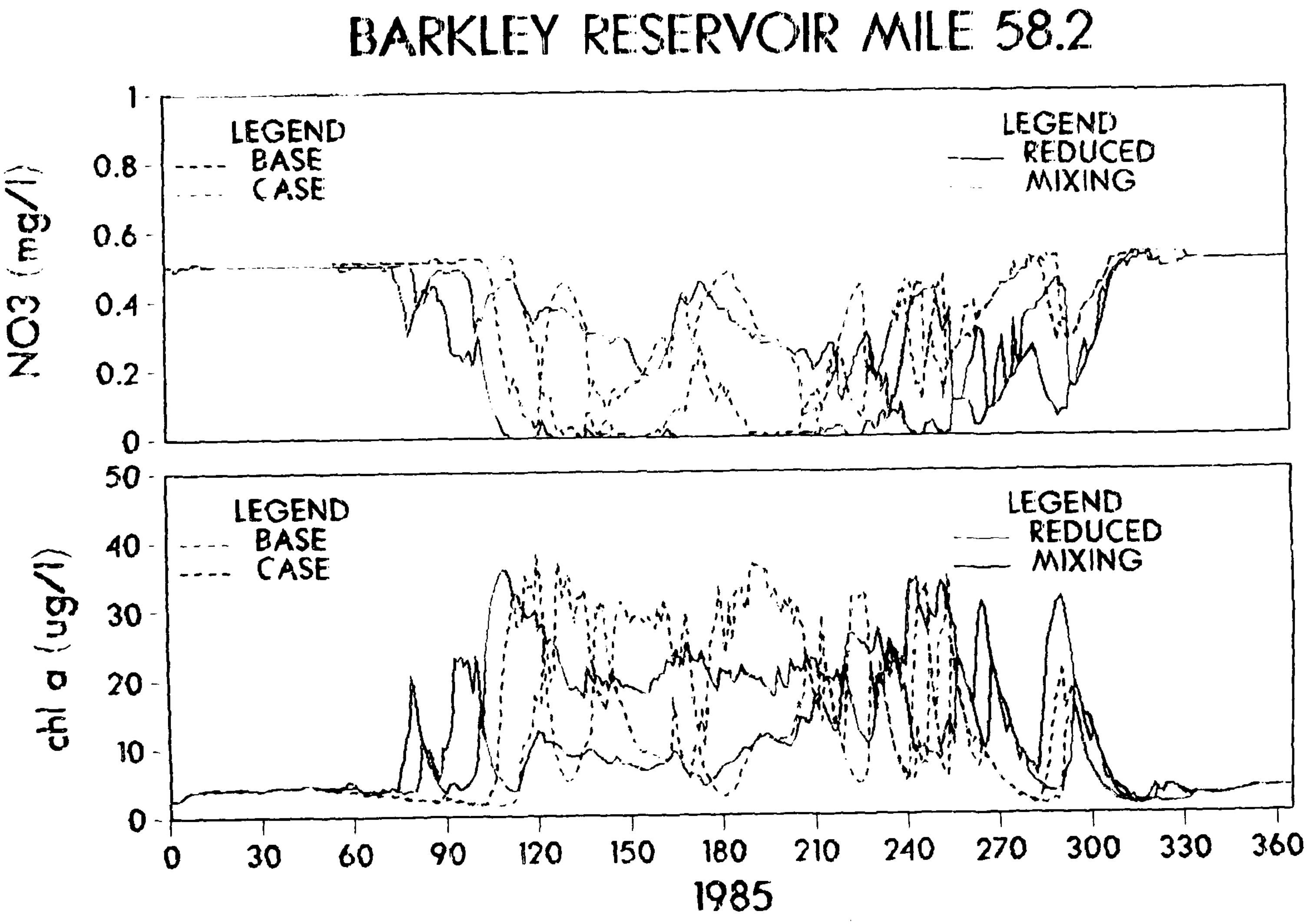

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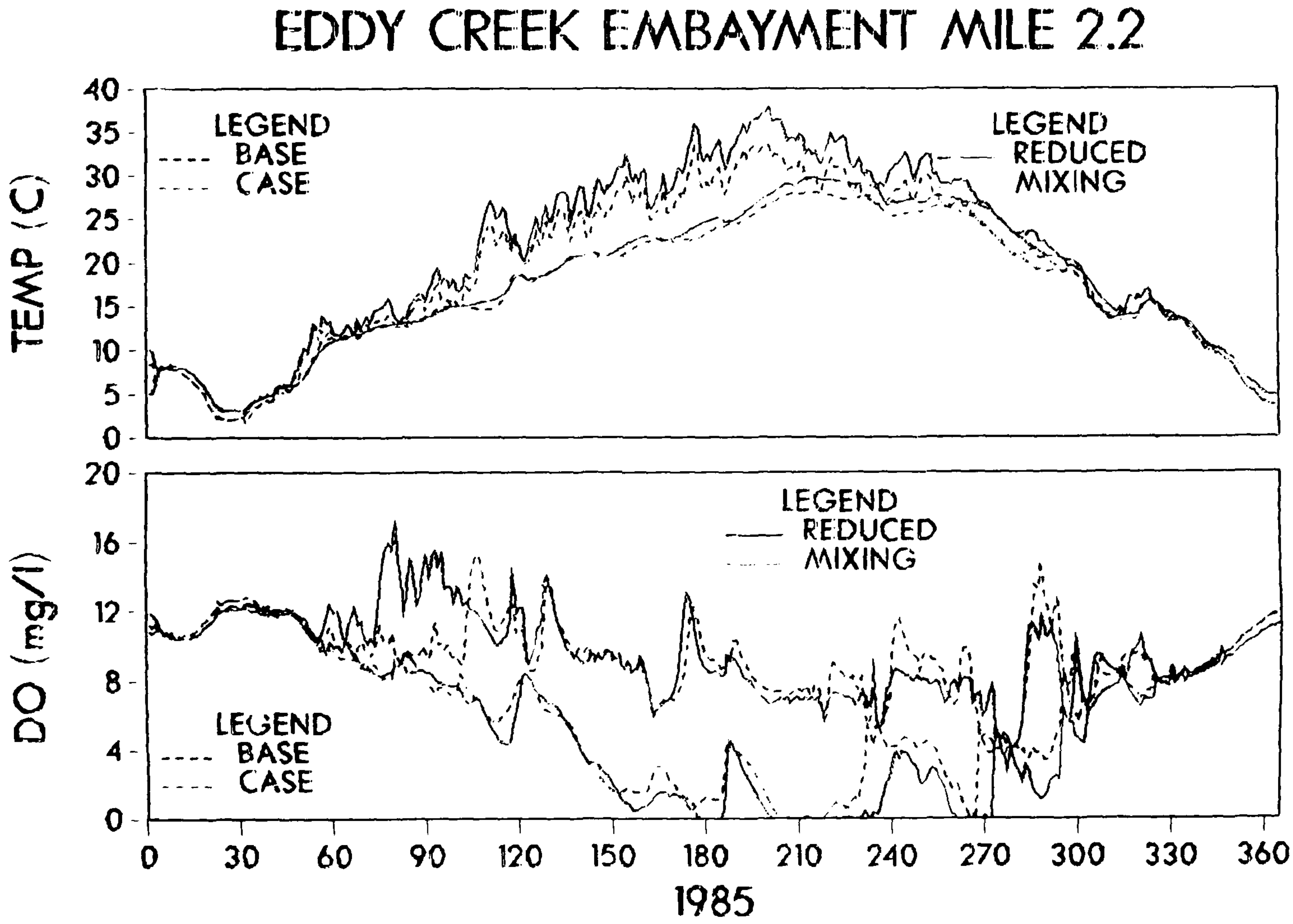
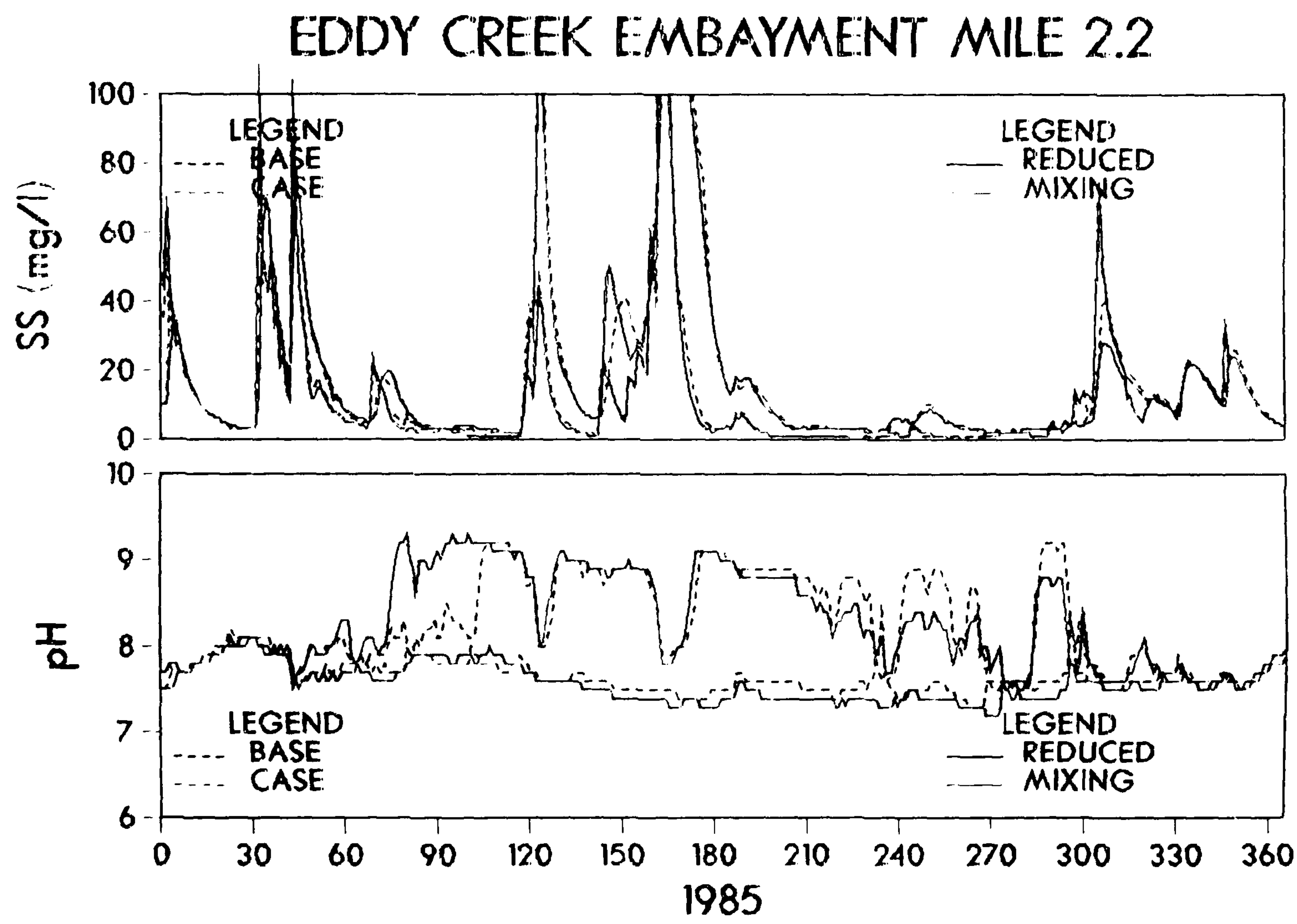


Figure 61 Simulated Effects of Reduced Mixing at Eddy Creek Mile 2.2



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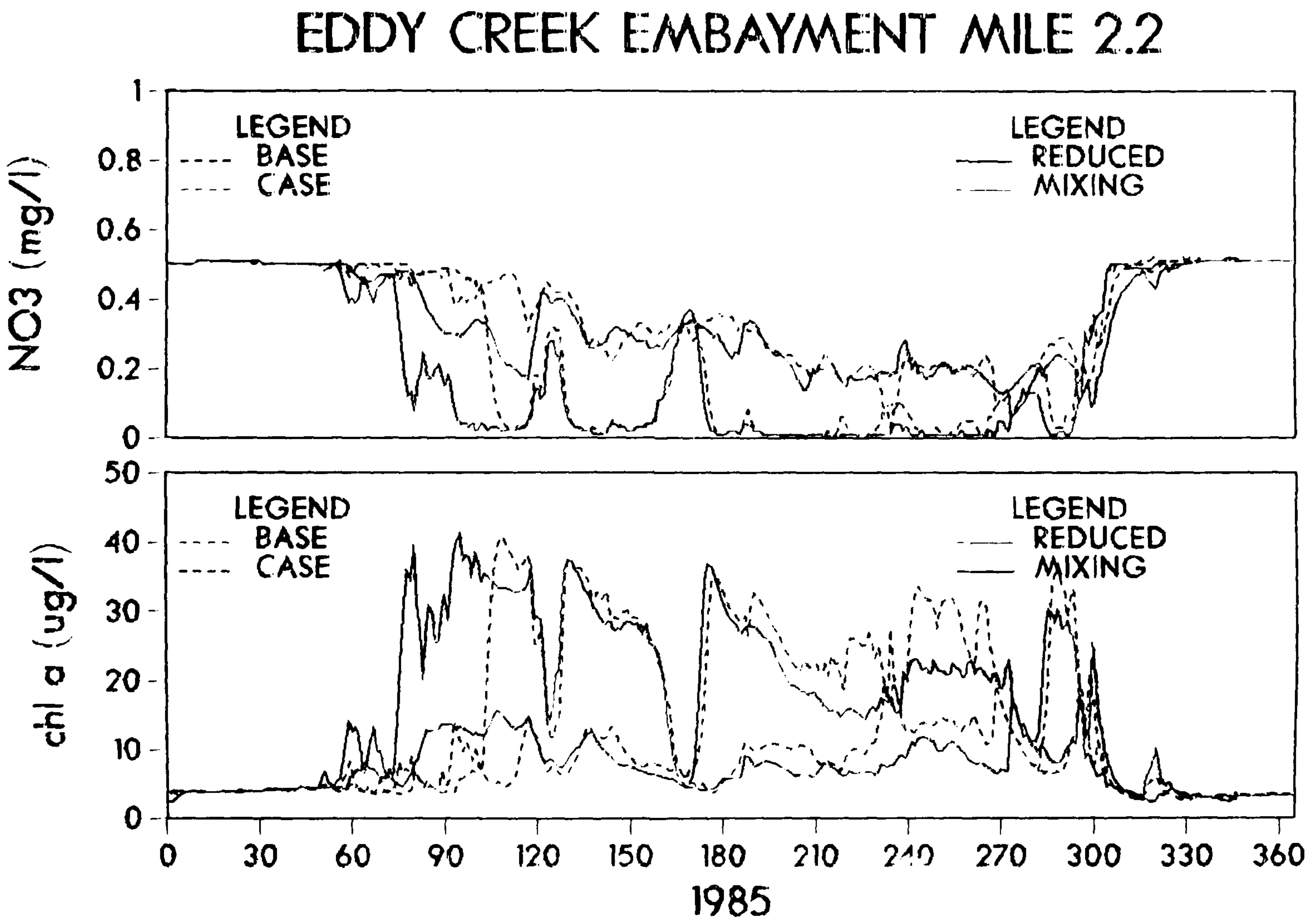

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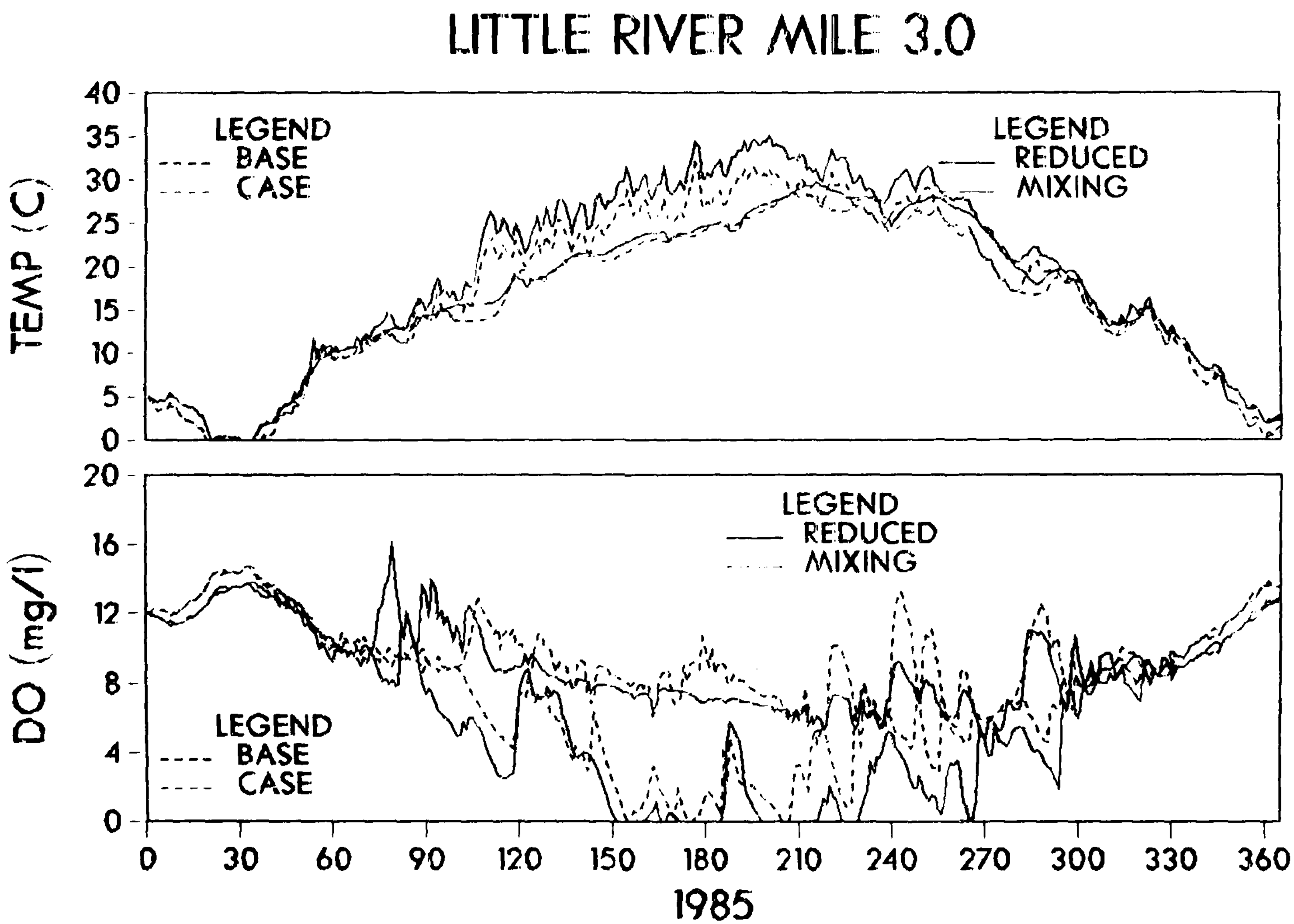
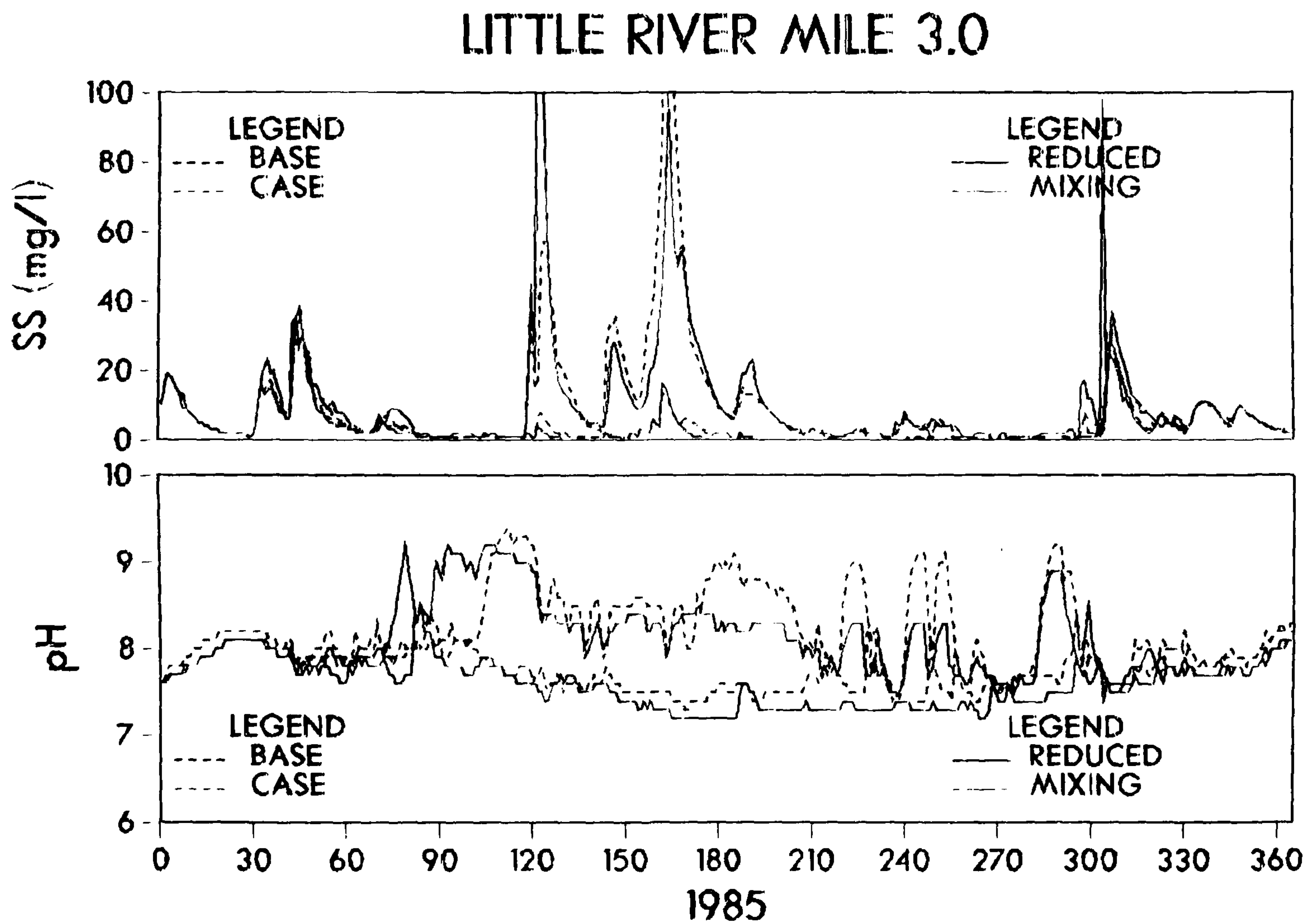


Figure 62 Simulated Effects of Reduced Mixing at Little River Mile 3.0



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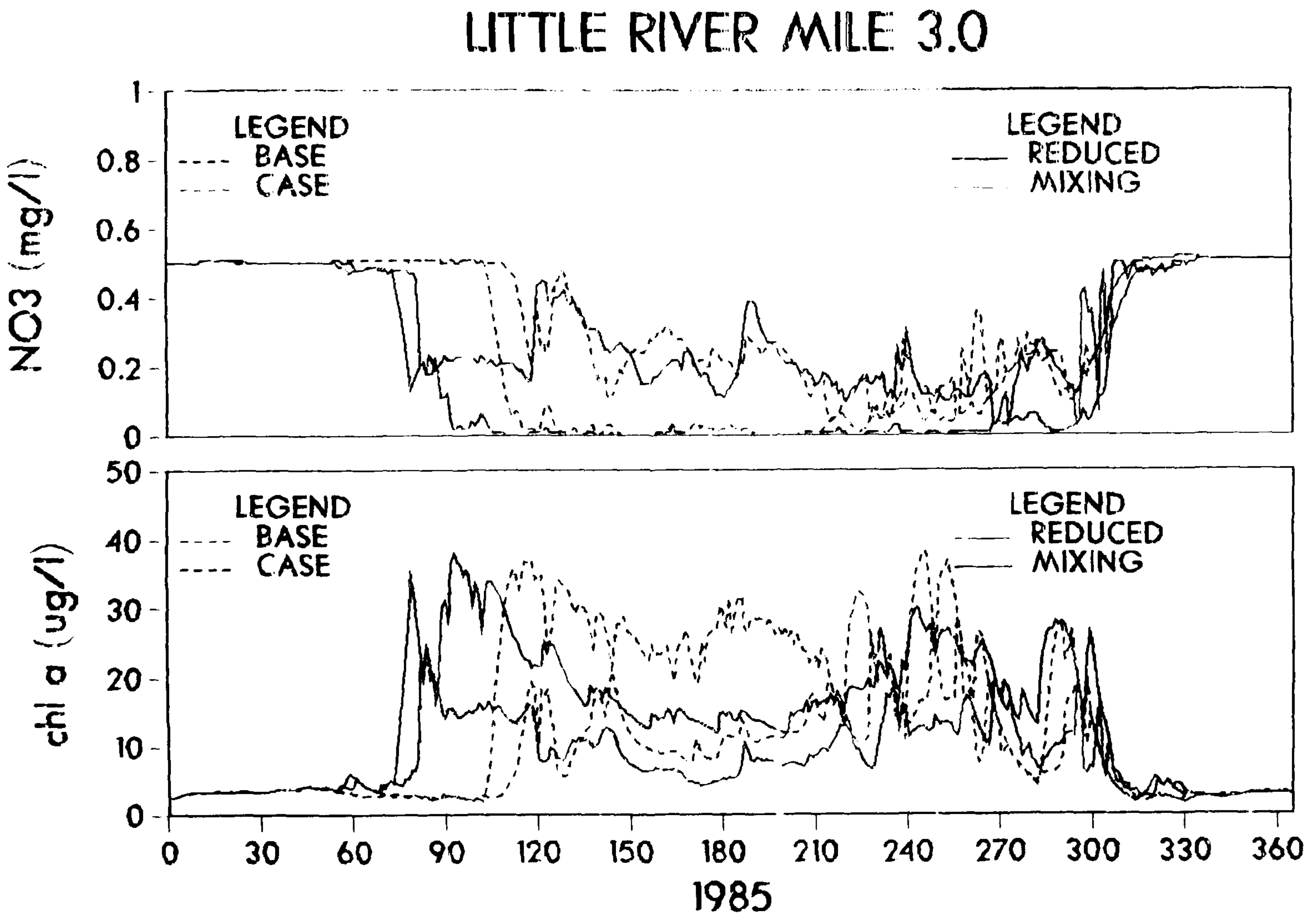


Figure 62 (continued)

$mg\text{-}O_2/m^2\text{-}day$. The sensitivity of the DO simulations to the SOD rates was further demonstrated by increasing the SOD values to twice the base case values, and also by setting the SOD rates to 0.0. The results from increasing the SOD rates are shown in Figure 63. The DO depletion at the bottom of each station was stronger during stratified conditions, with the magnitude of the additional DO depletion dependent on the duration of the stratification period. The maximum DO decreases were approximately 2 mg/L, and the periods of anoxic conditions were increased at all stations.

The effects from zero SOD are shown in Figure 64. The bottom DO concentrations were increased significantly above the base case at all stations. The magnitude of the increase was dependent on the duration of the stratified period and the station location. In the main channel, the maximum increases in DO were approximately 3 mg/L. In Eddy Creek, the DO increases were approximately 2-3 mg/L; while in the Little River embayment, the DO increases were 4-5 mg/L. Since residence times were similar for the two embayments, the differences were apparently the result of greater mud to volume ratios (geometry) in Little River.

Effects of Nutrients Algal Productivity

The sensitivity of water quality in Lake Barkley to algal production was tested by increasing the nutrient inflow concentrations to allow more algal growth, and by reducing the nutrient inflows to limit algal growth. The limiting nutrient was nitrogen in all cases, since the inflow N:P ratio of was less than the biomass content N:P ratio of 15. The results of the increased nutrient case are shown in Figures 65 to 68. Surface DO concentrations were increased from the additional algal productivity, while bottom DO concentrations were reduced slightly from the increased respiration. Surface pH values were increased during

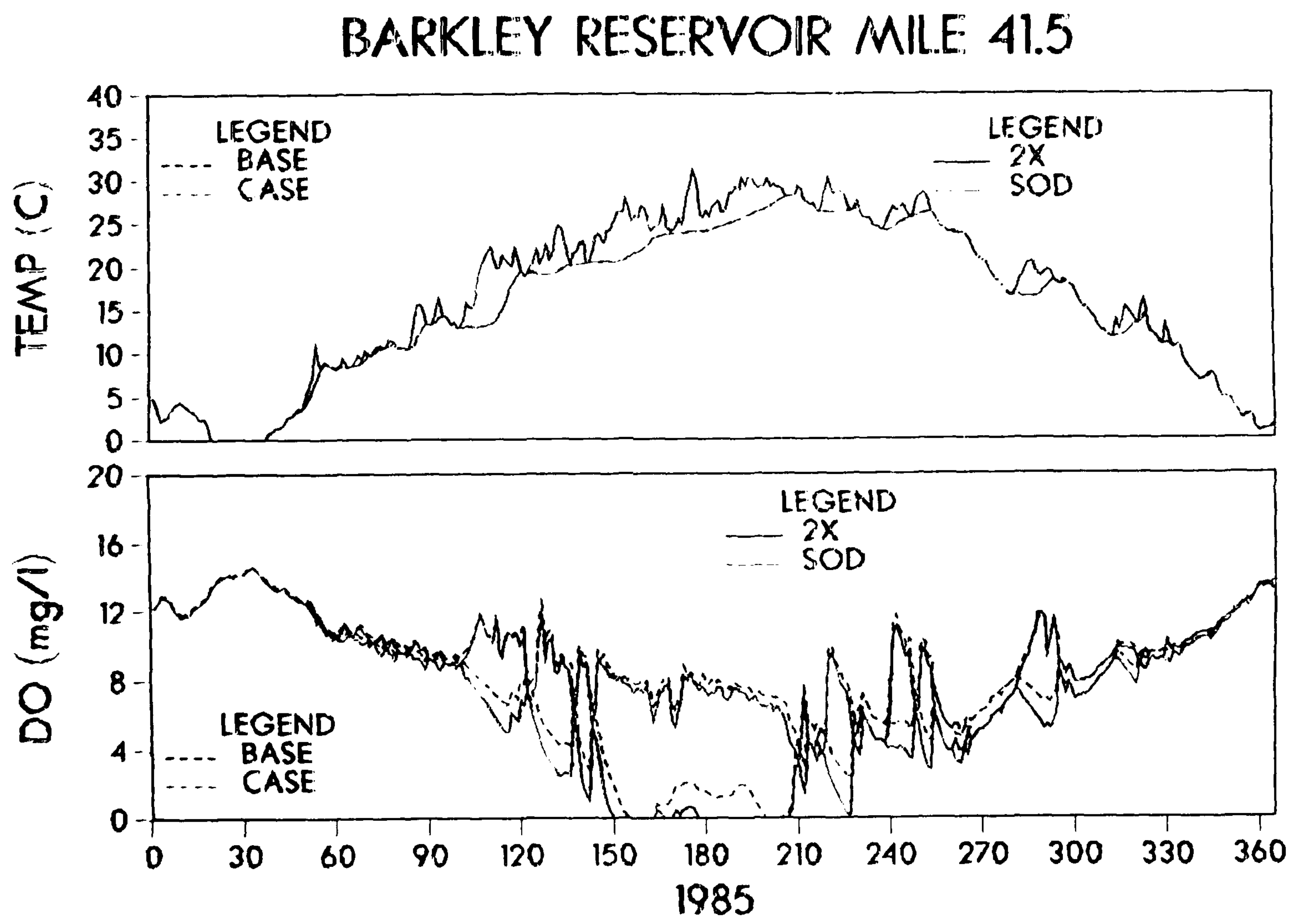
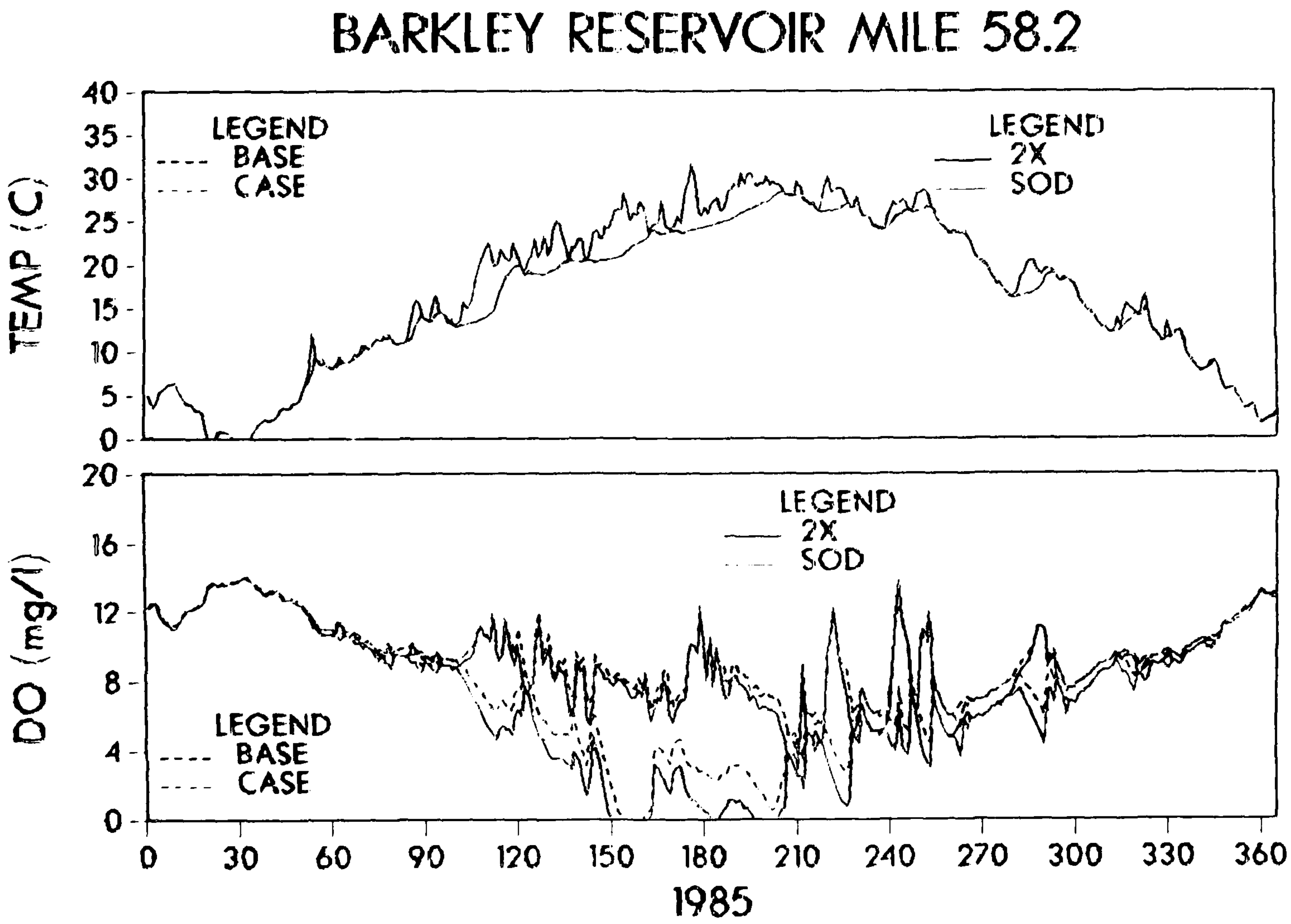


Figure 63 Simulated Effects of Increased SOD Rates



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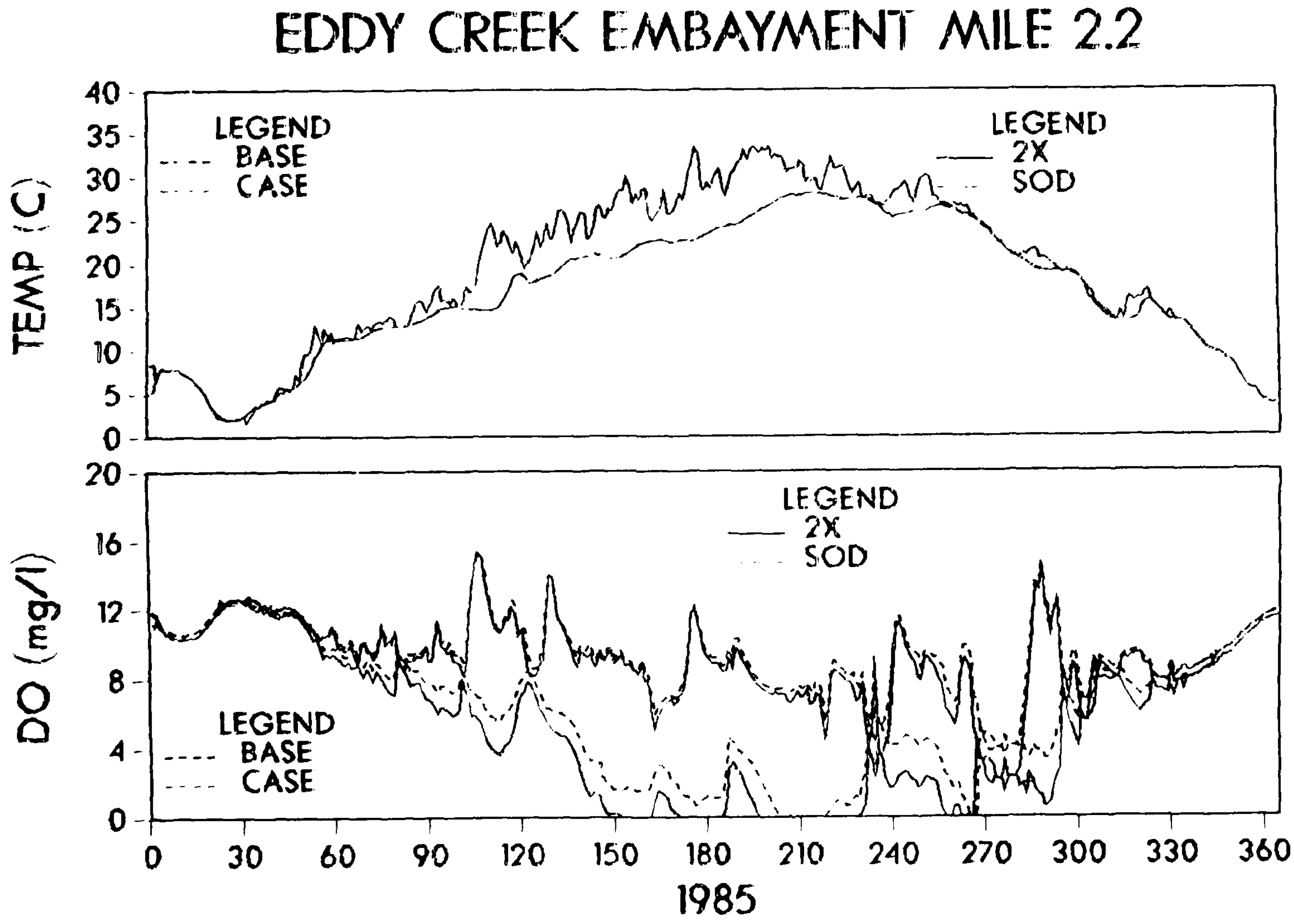

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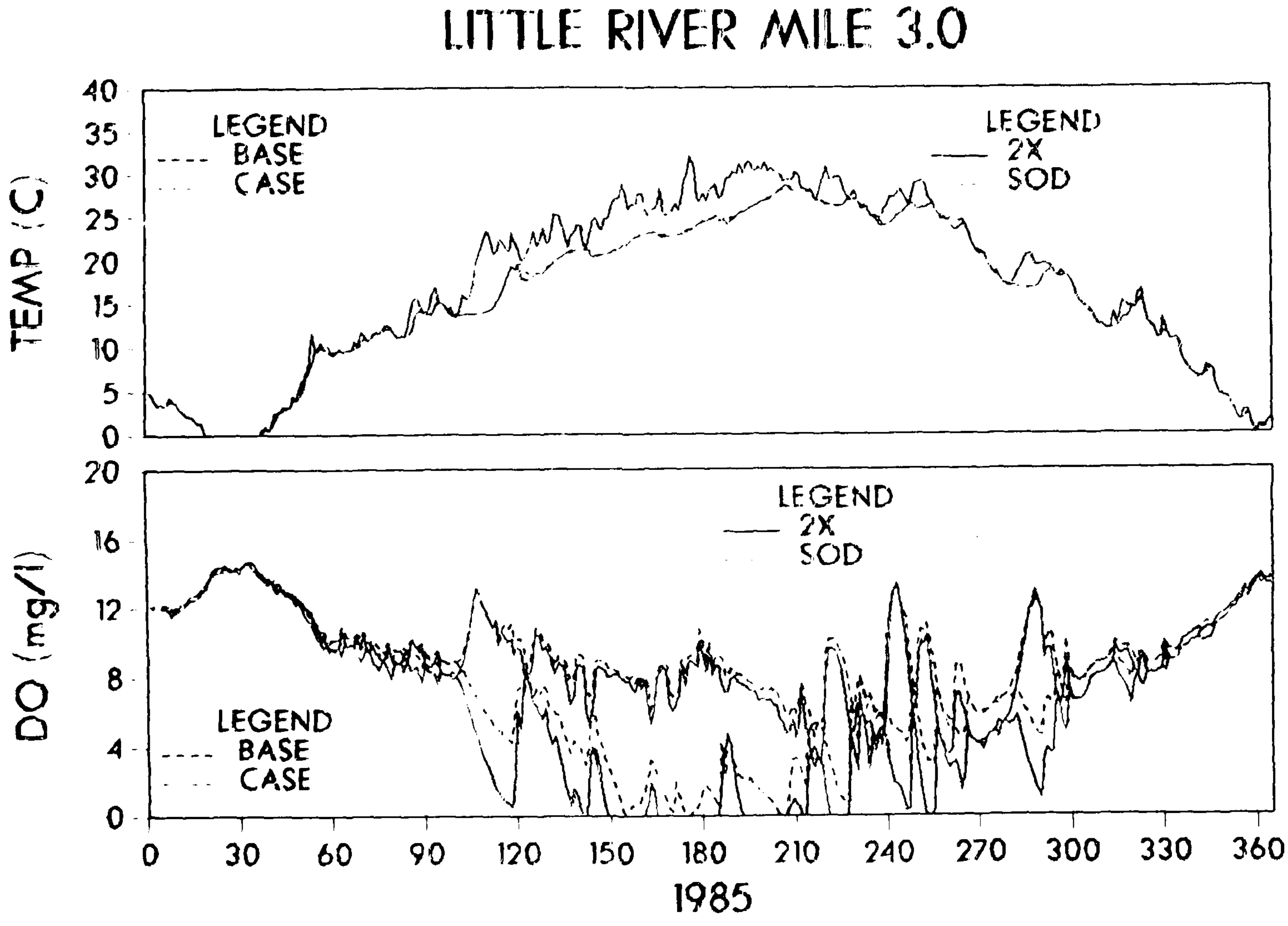


Figure 63 (continued)

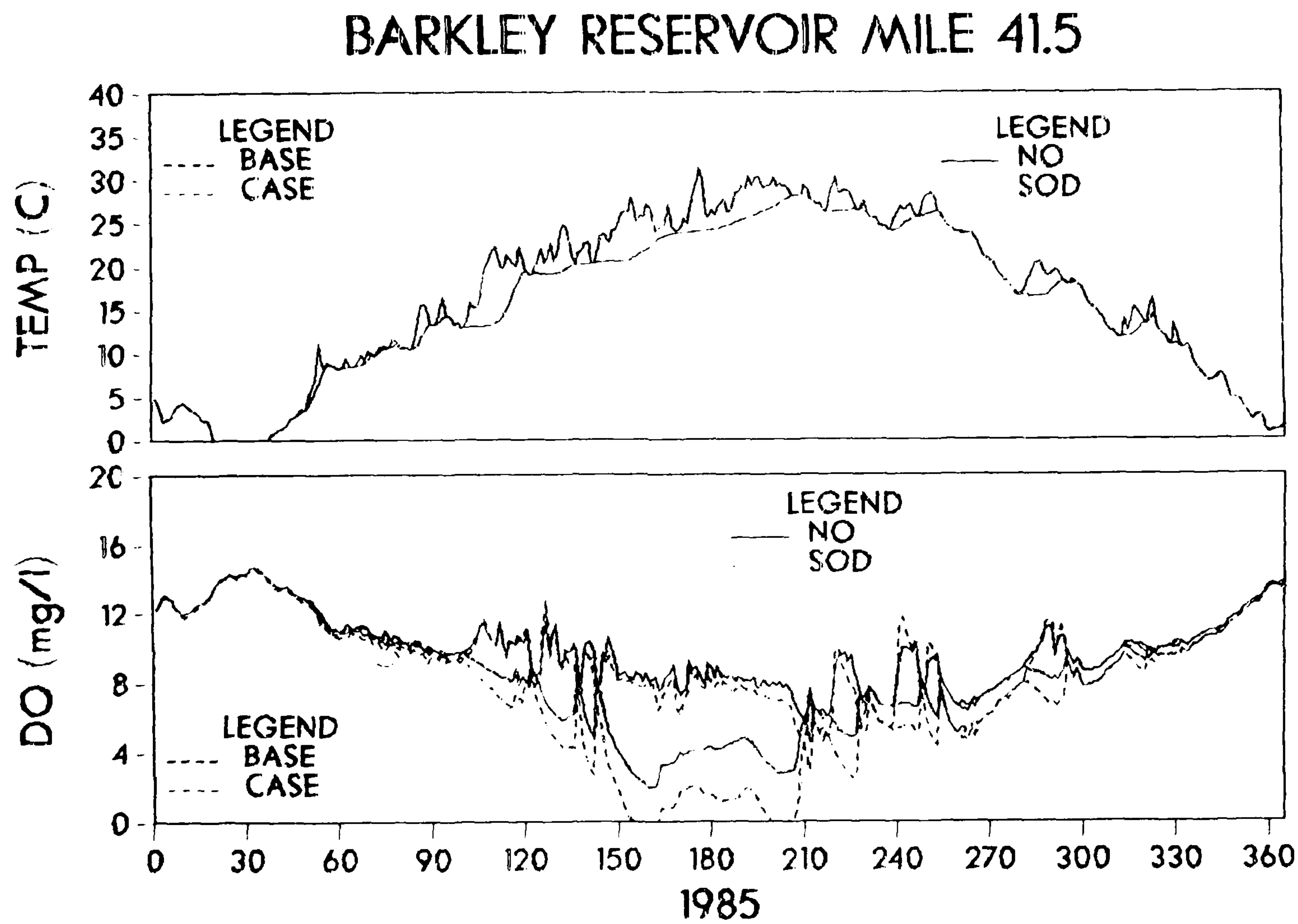
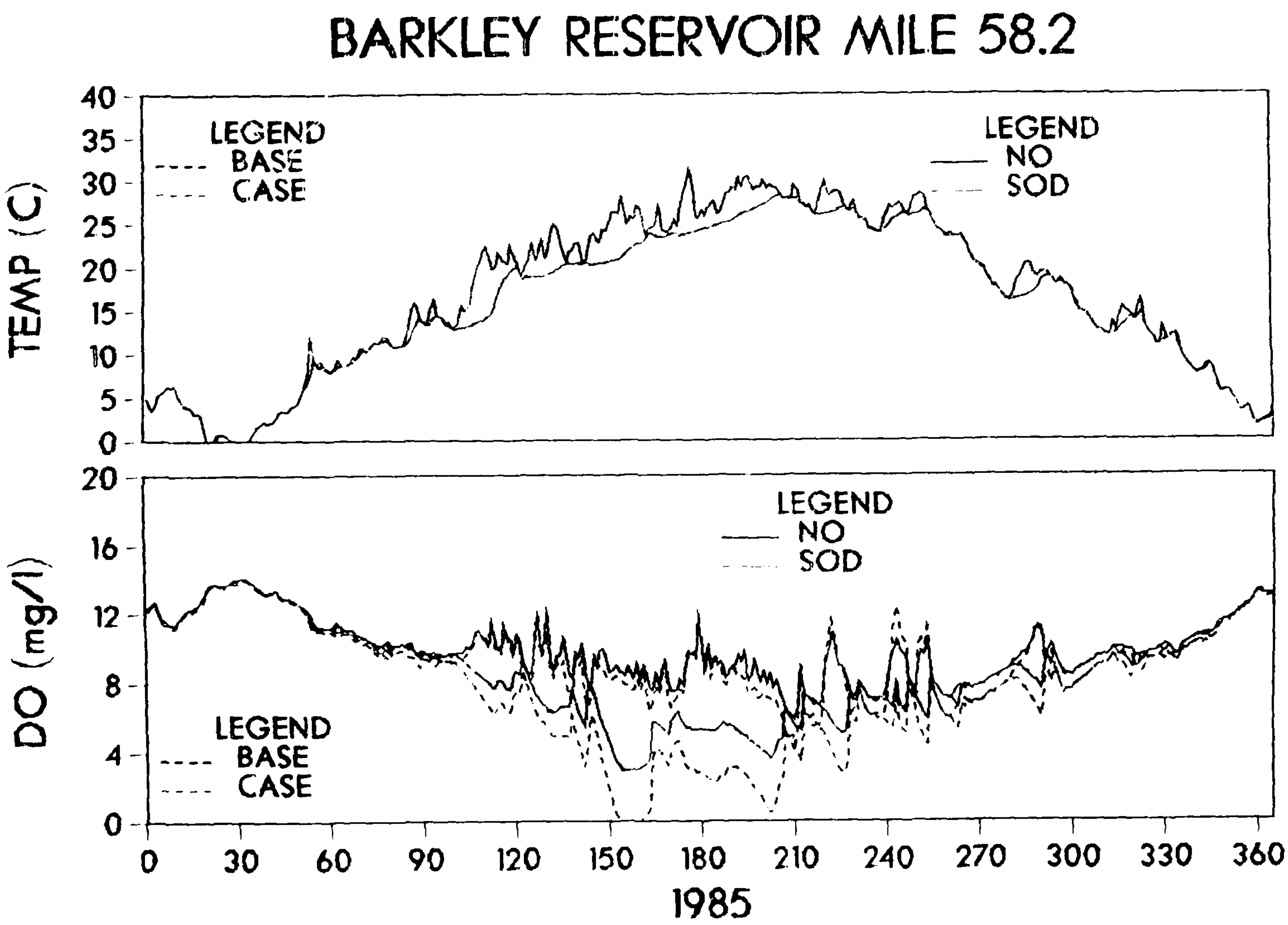


Figure 64 Simulated Effects of Reduced SOD Rates



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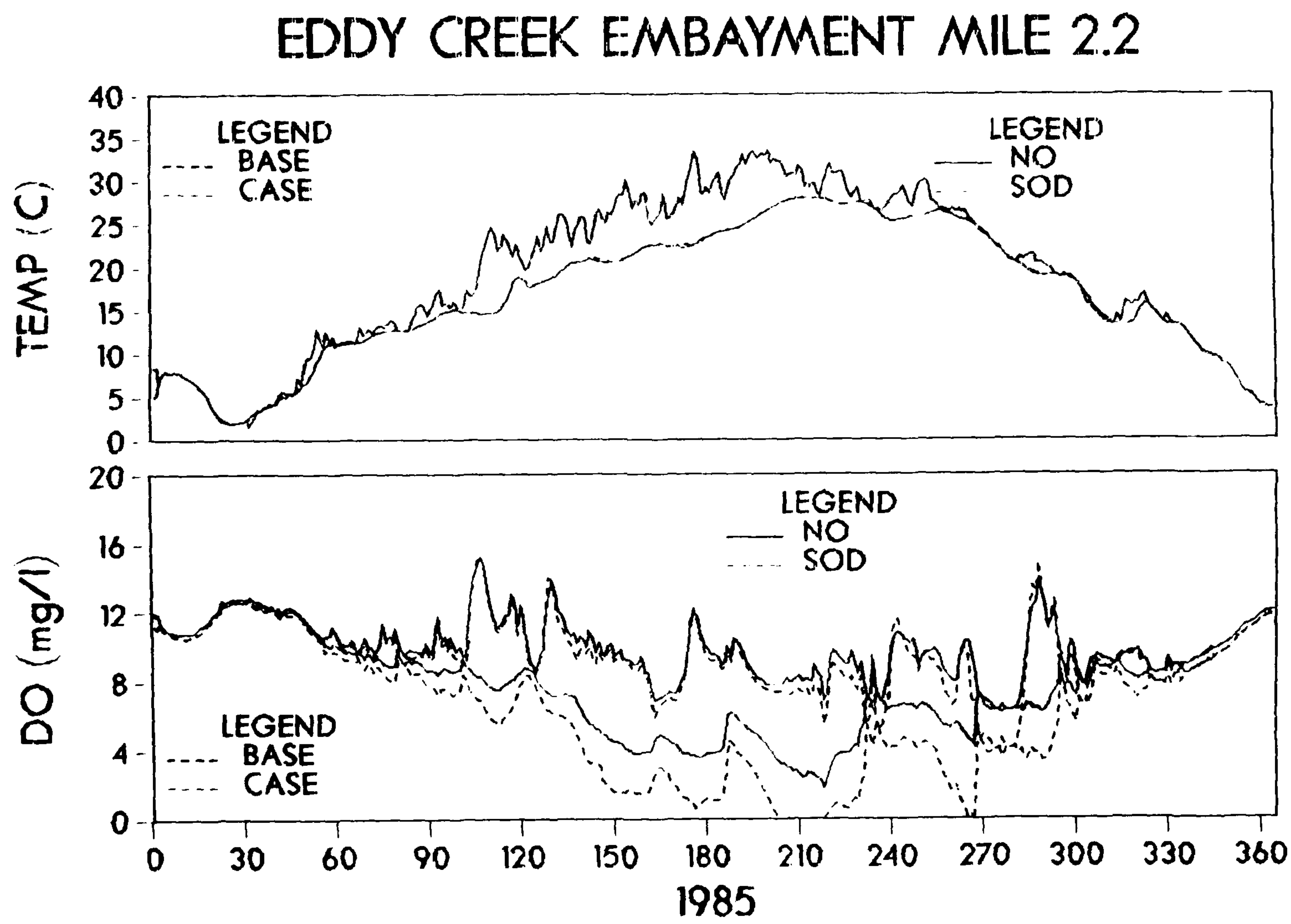

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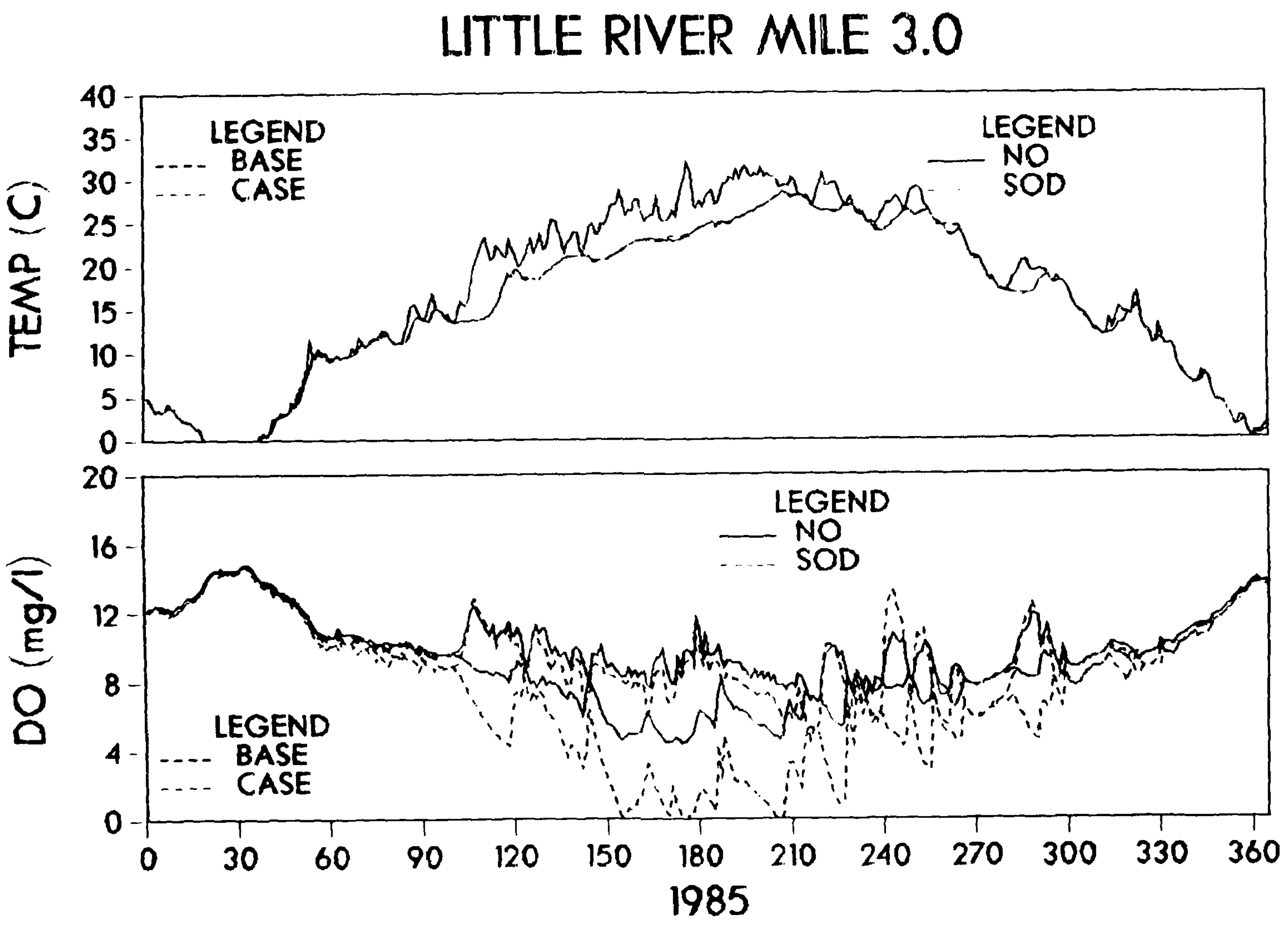

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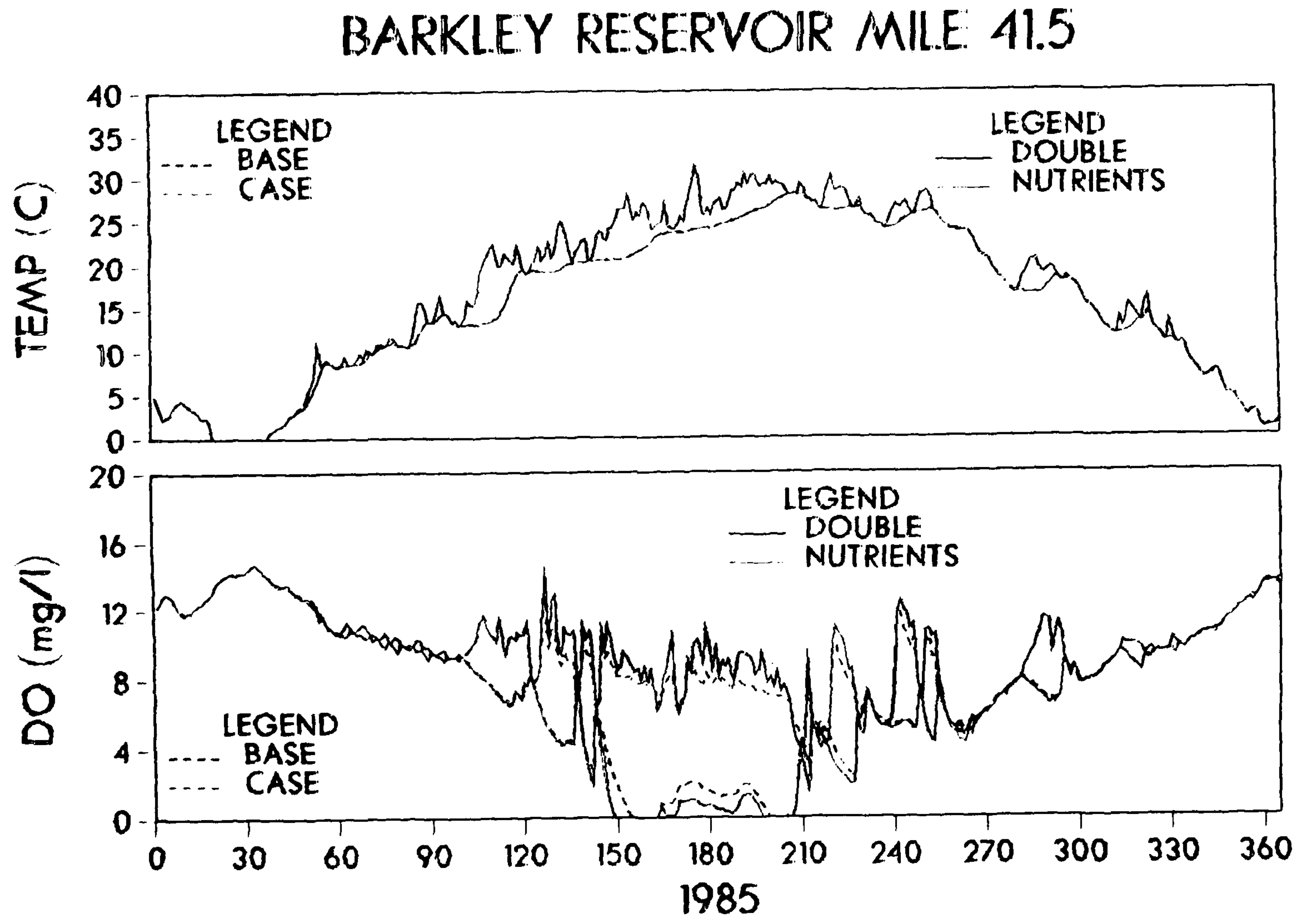
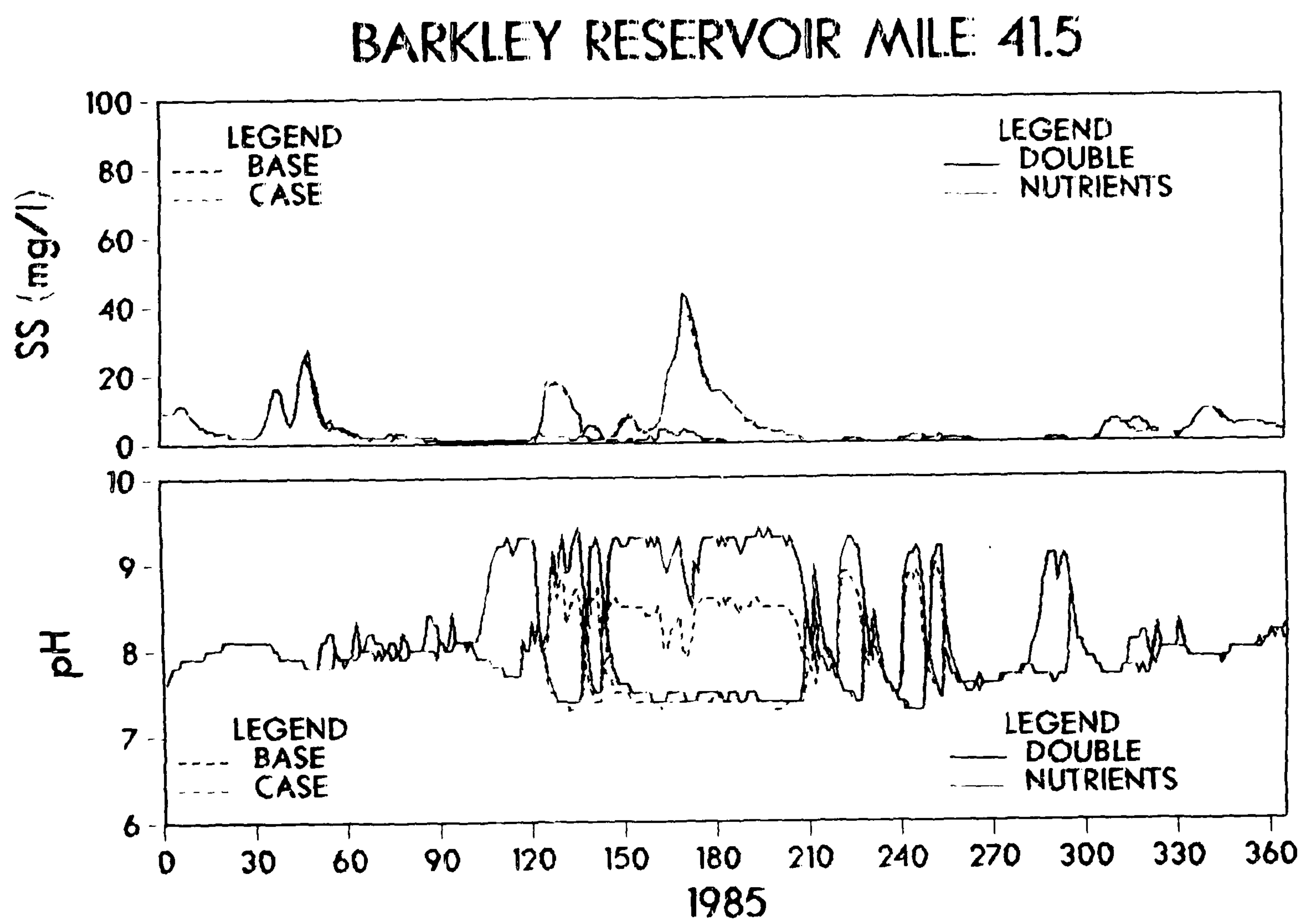


Figure 65 Simulated Effects of Increased Nutrients at CuRM 41.5



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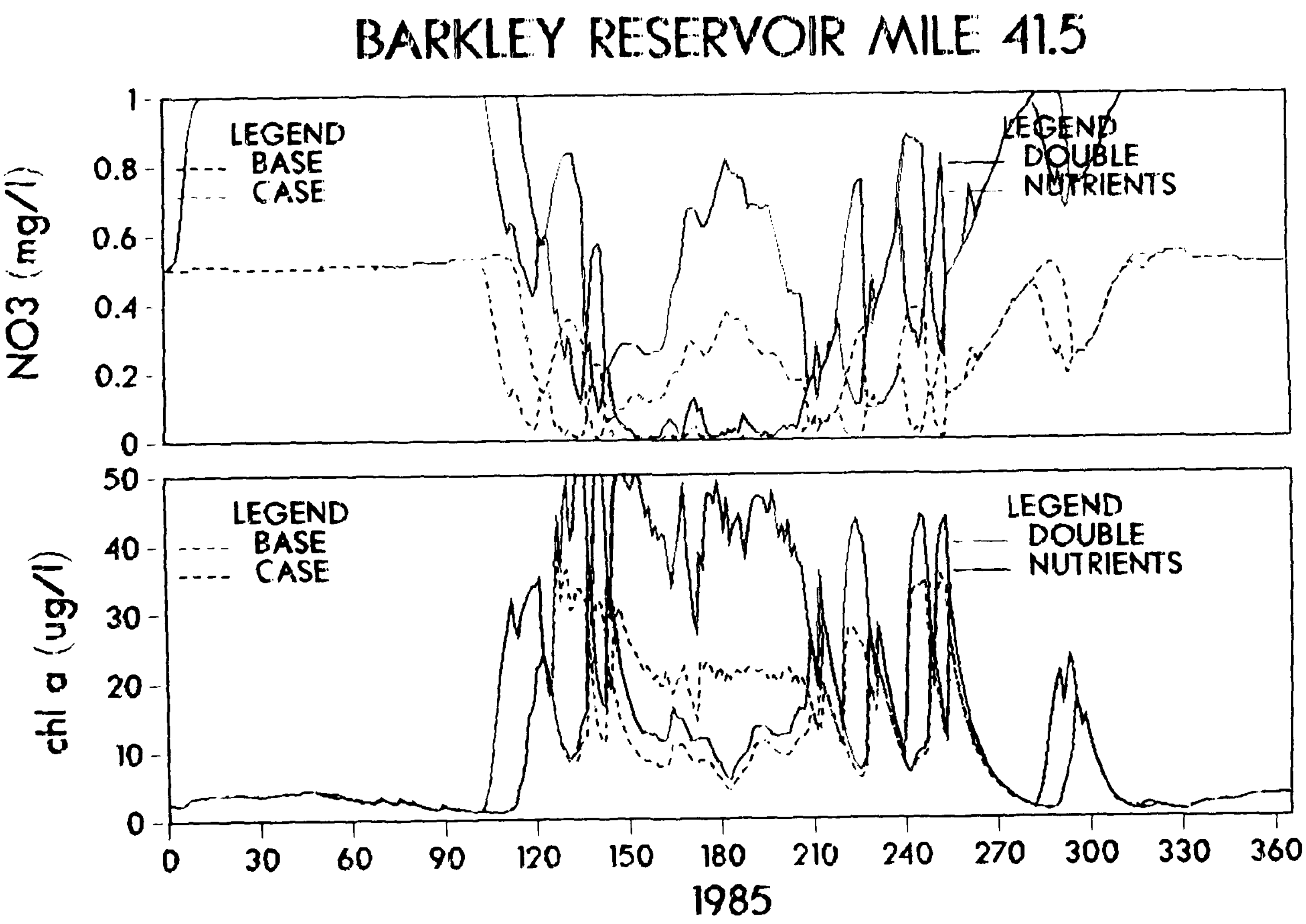

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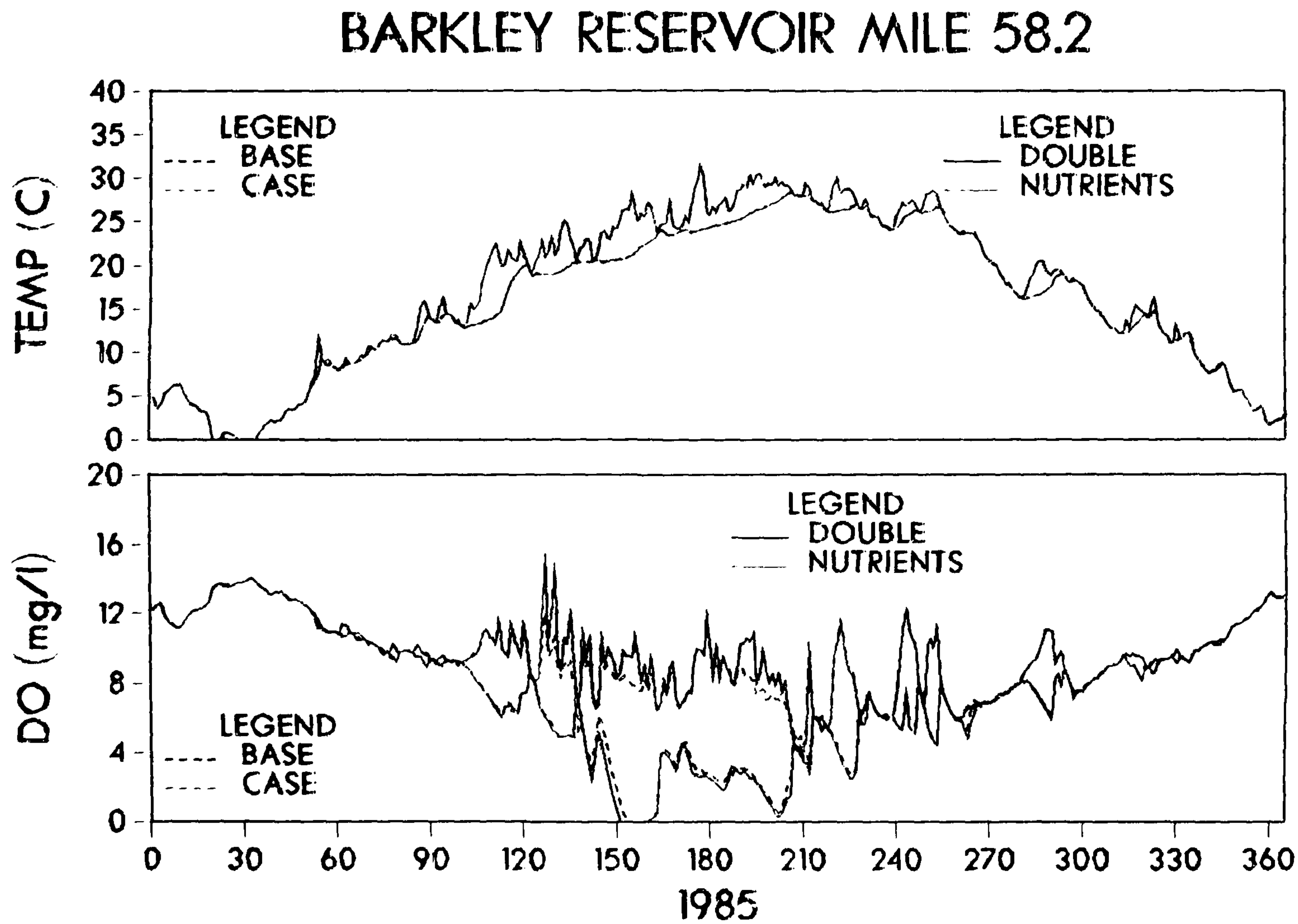
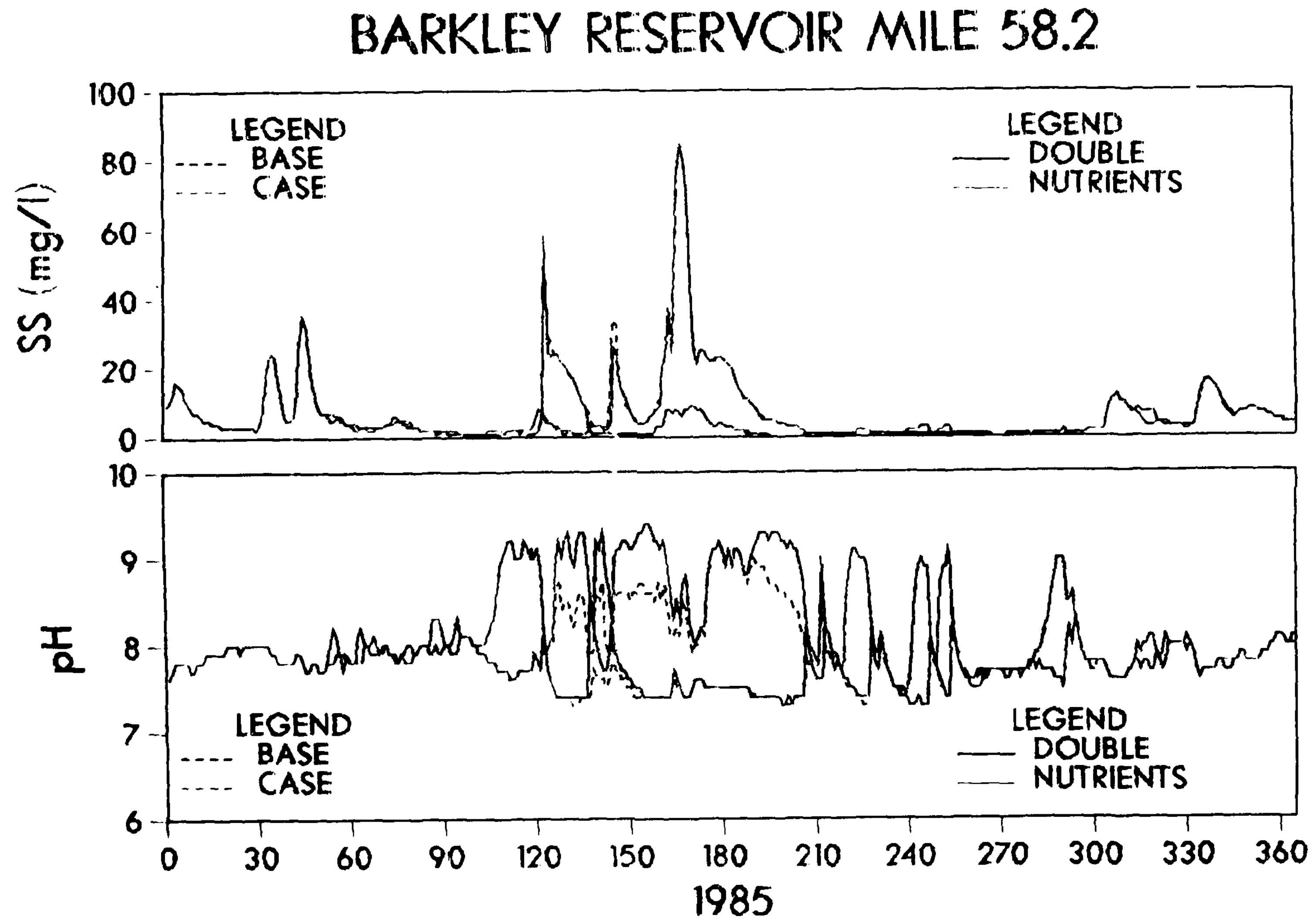


Figure 66 Simulated Effects of Increased Nutrients at CuRM 58.2



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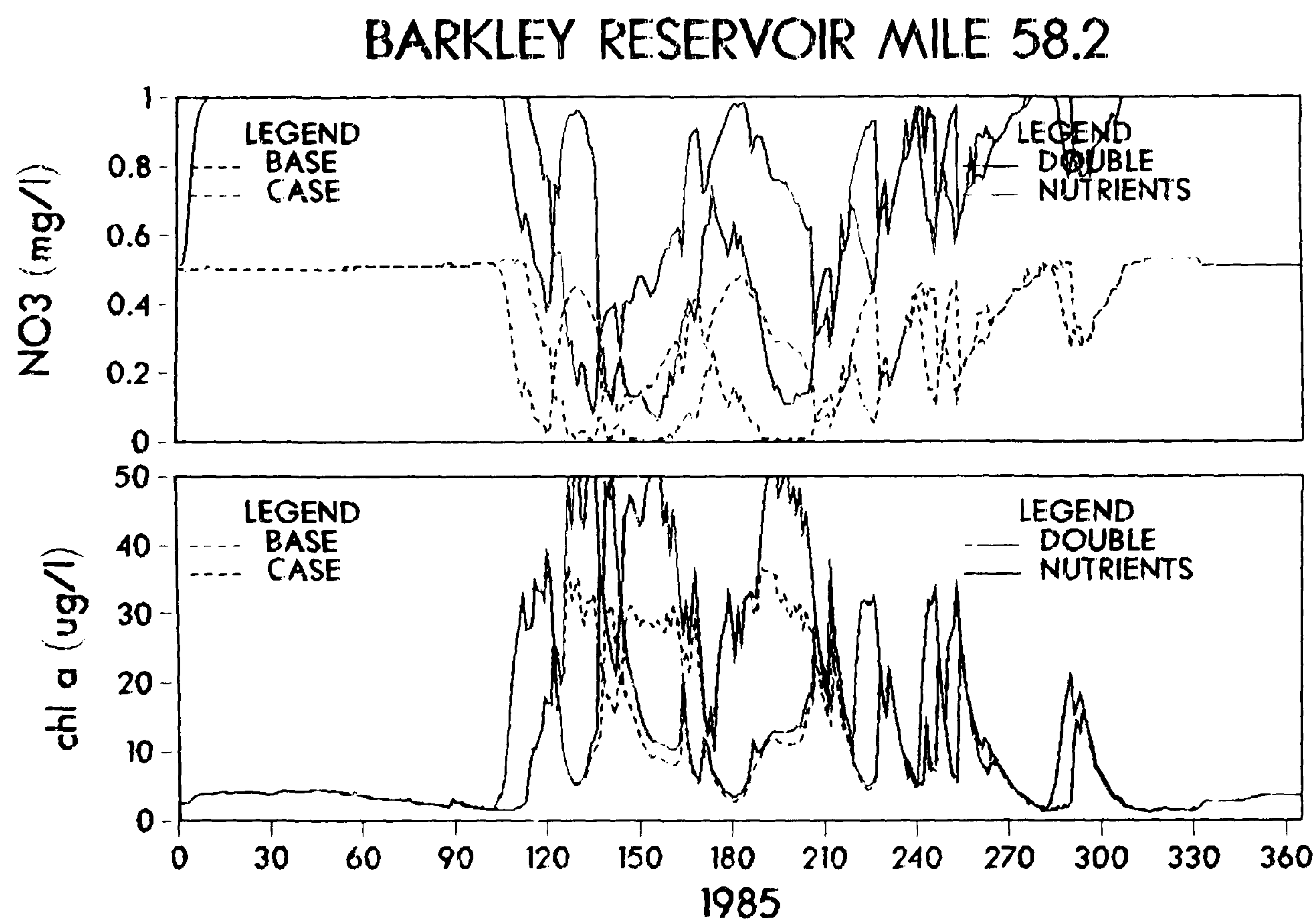

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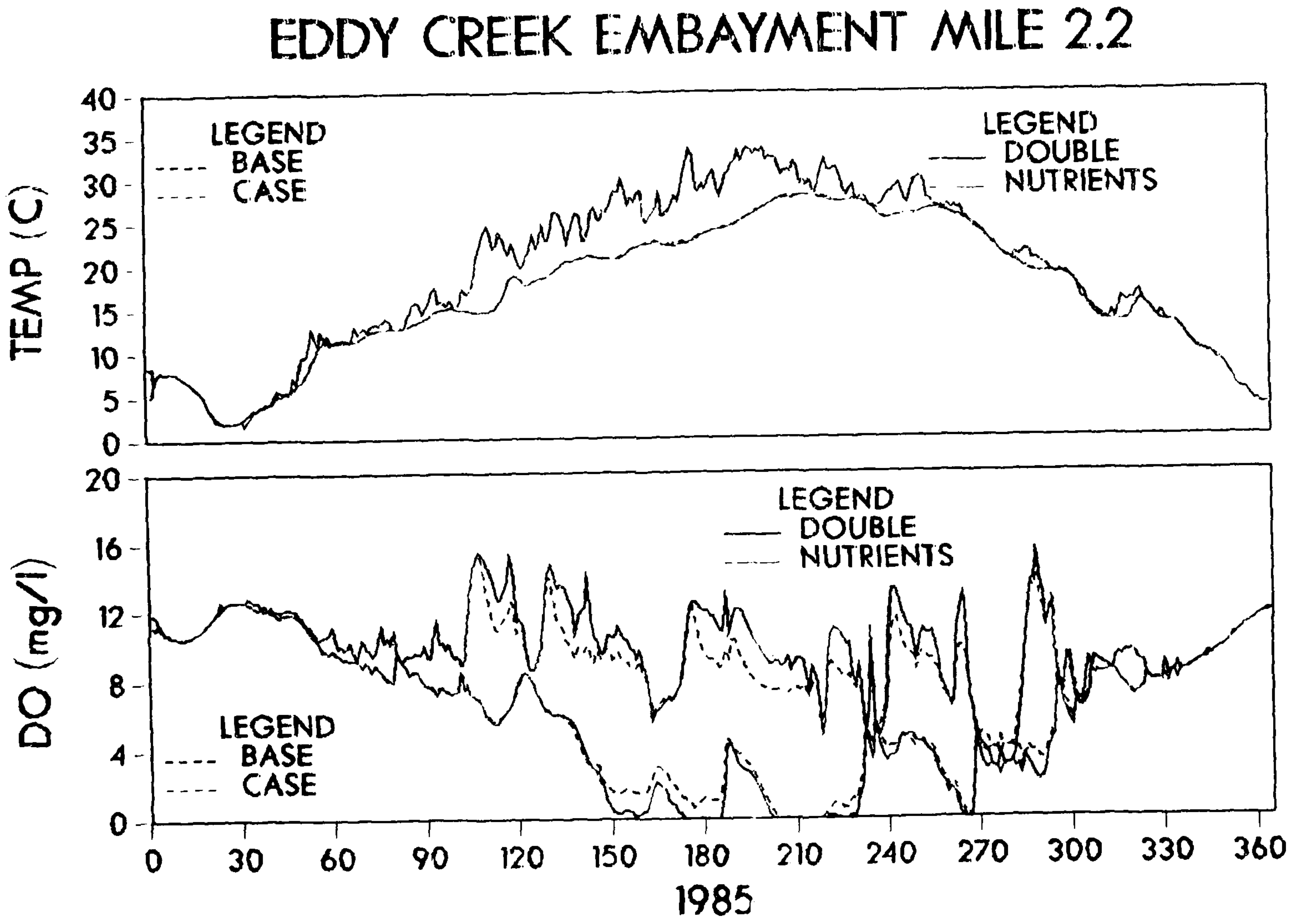
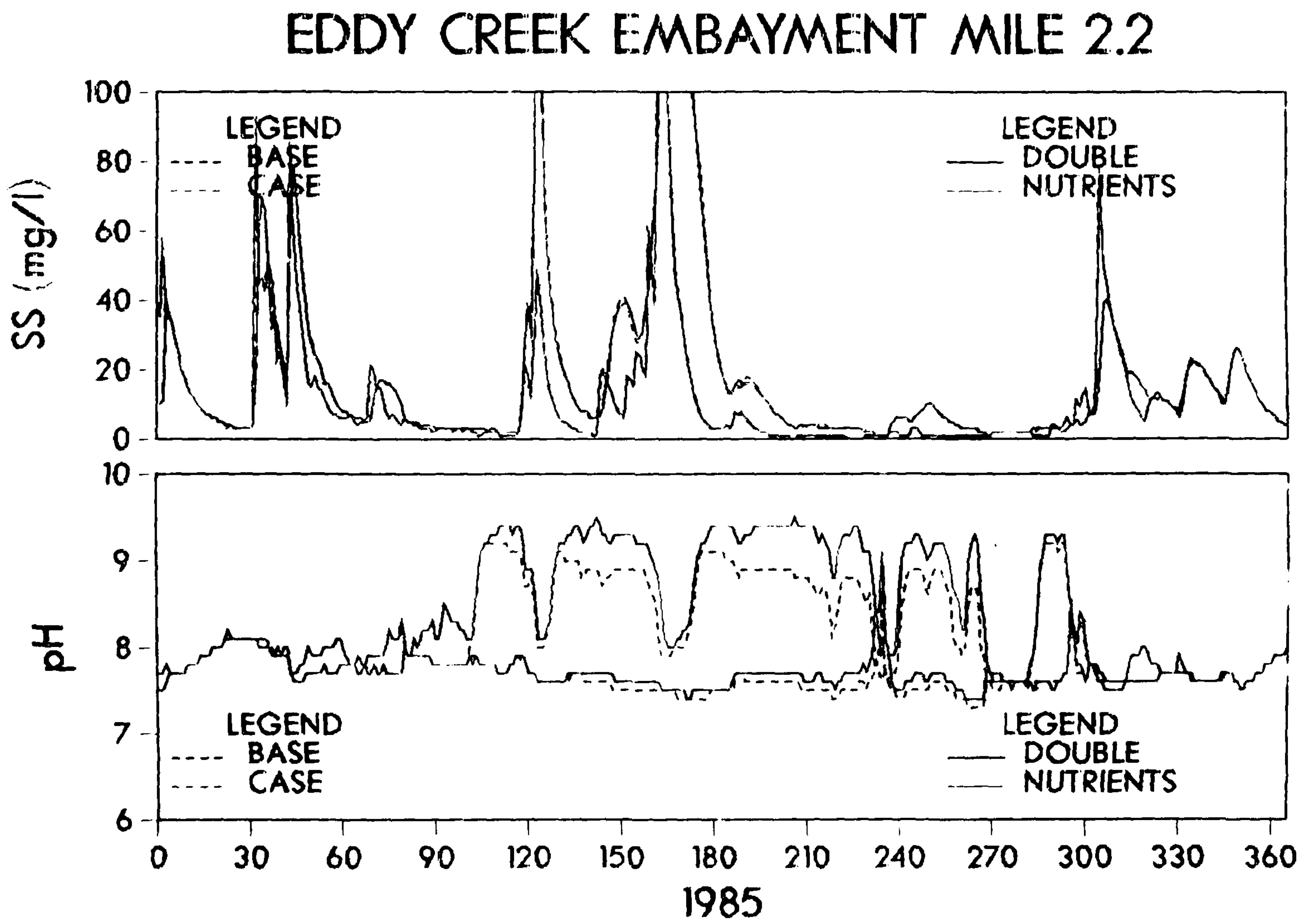


Figure 67 Simulated Effects of Increased Nutrients at Eddy Creek Mile 2.2



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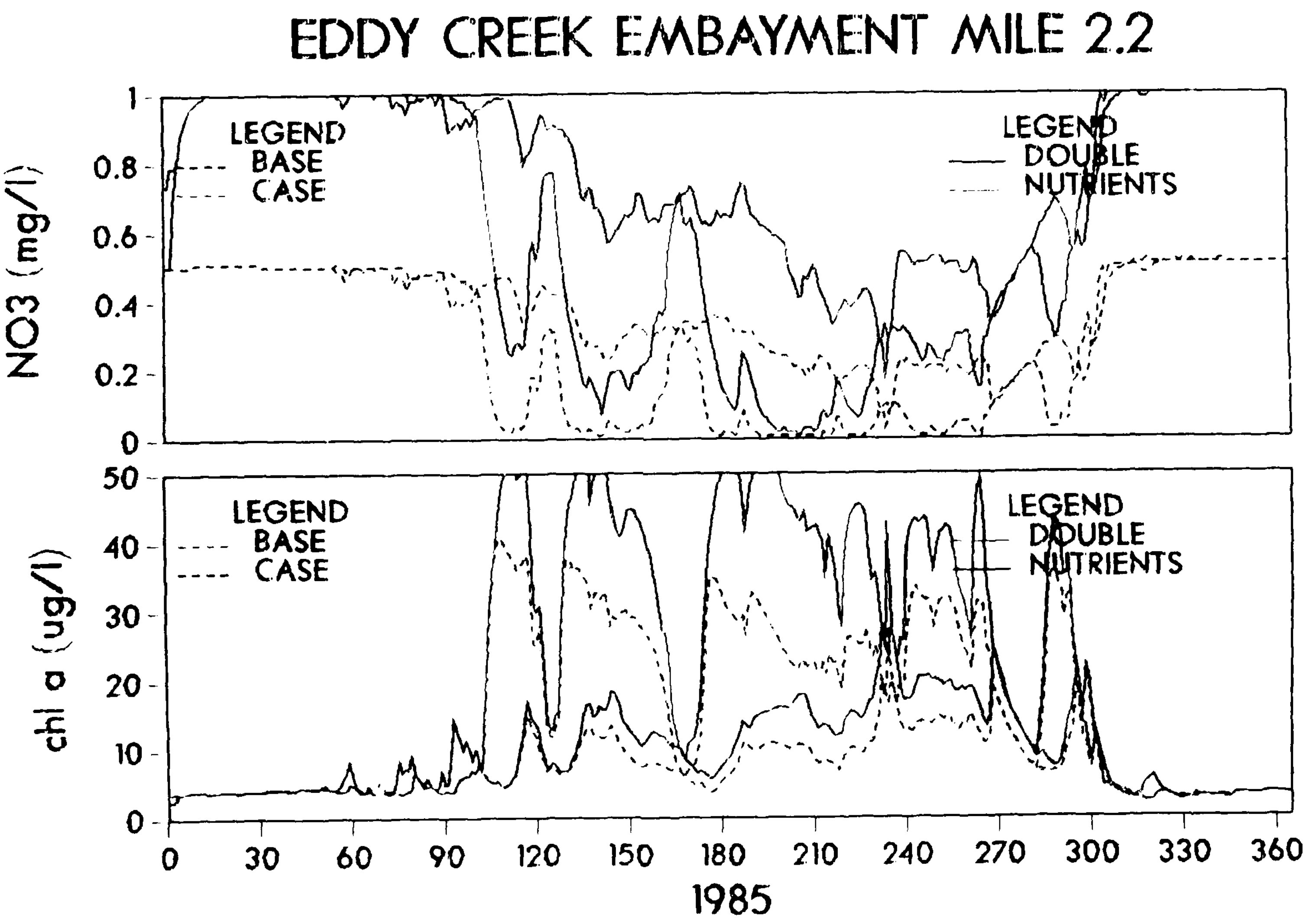

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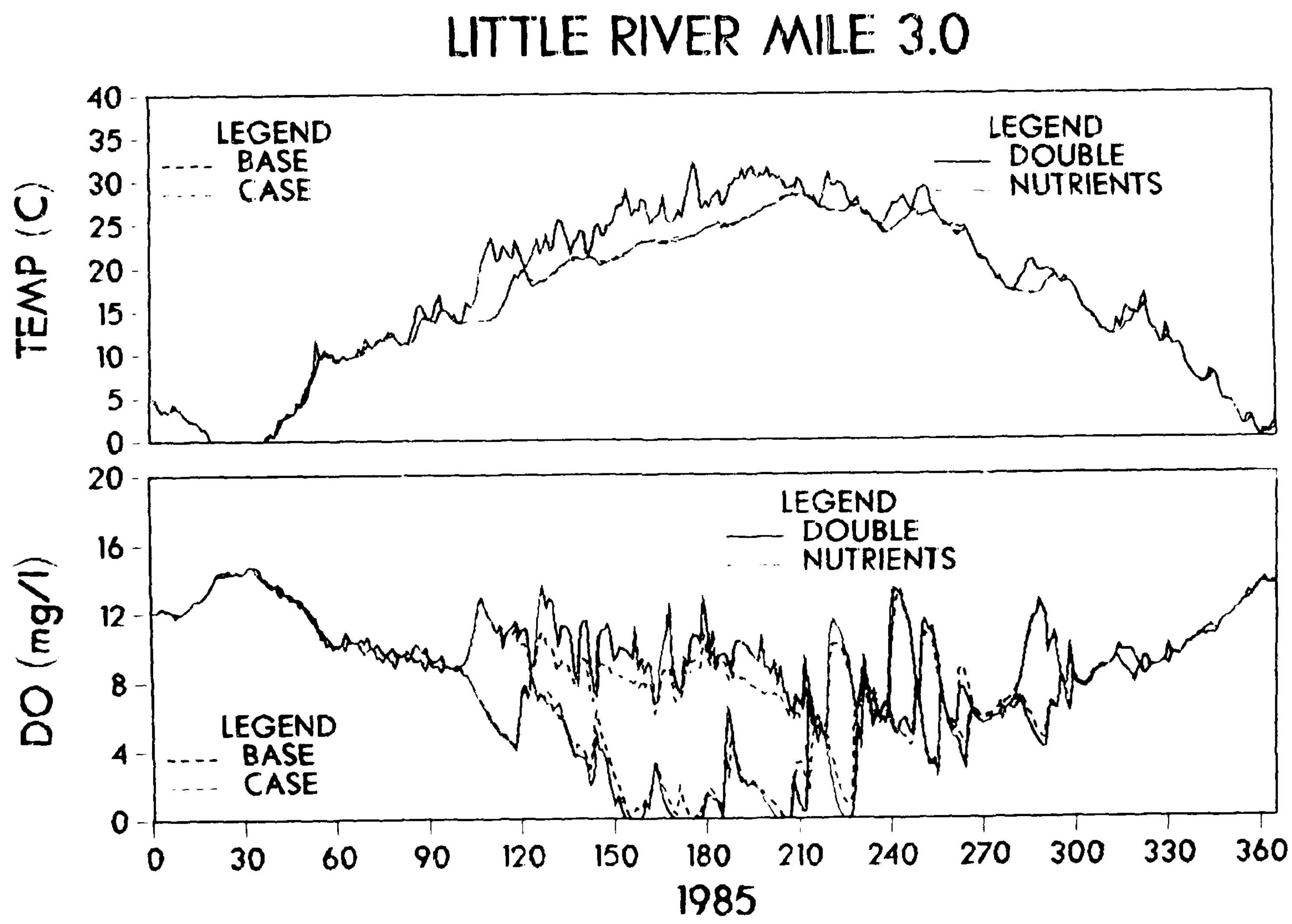
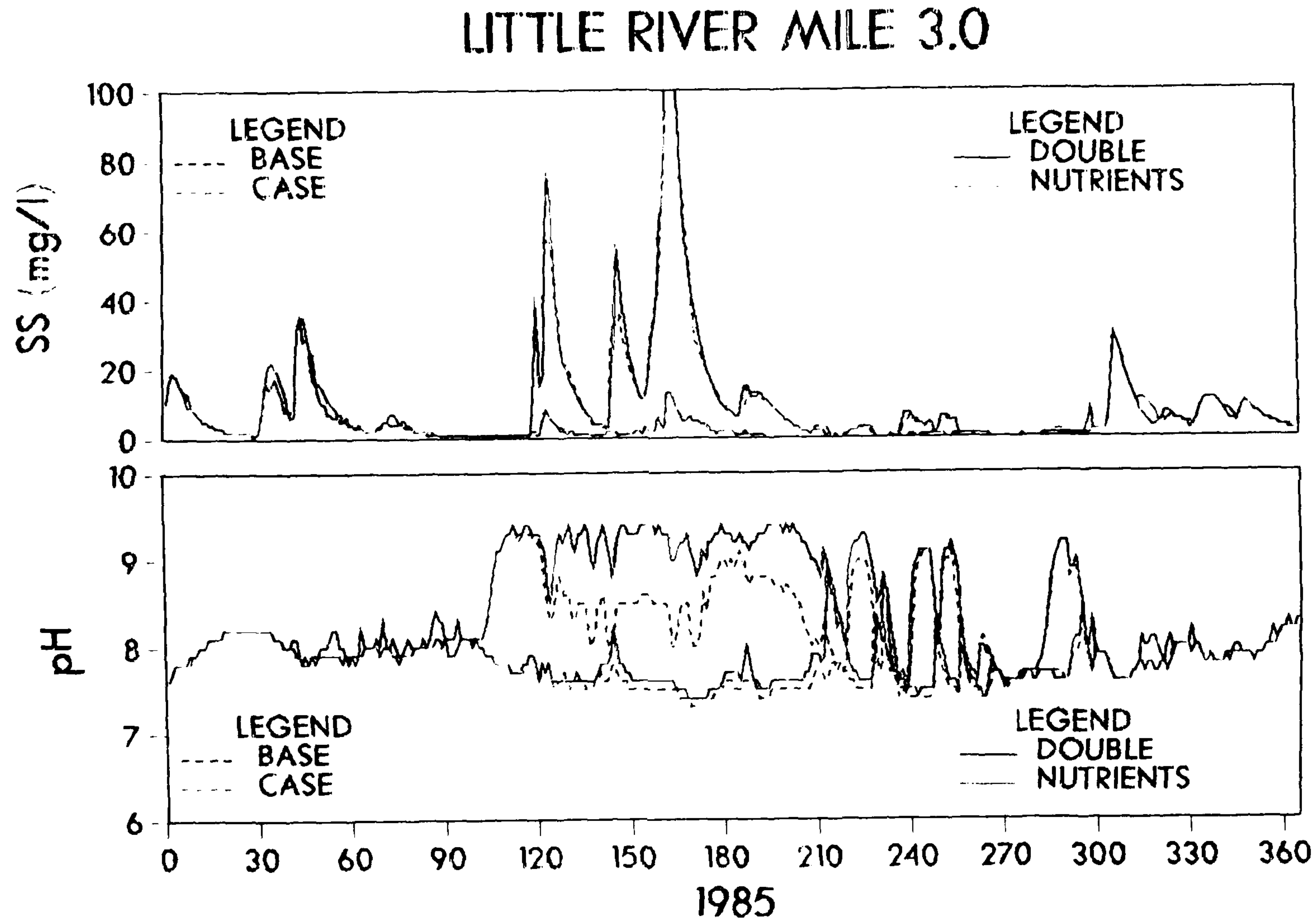


Figure 68 Simulated Effects of Increased Nutrients at Little River Mile 3.0



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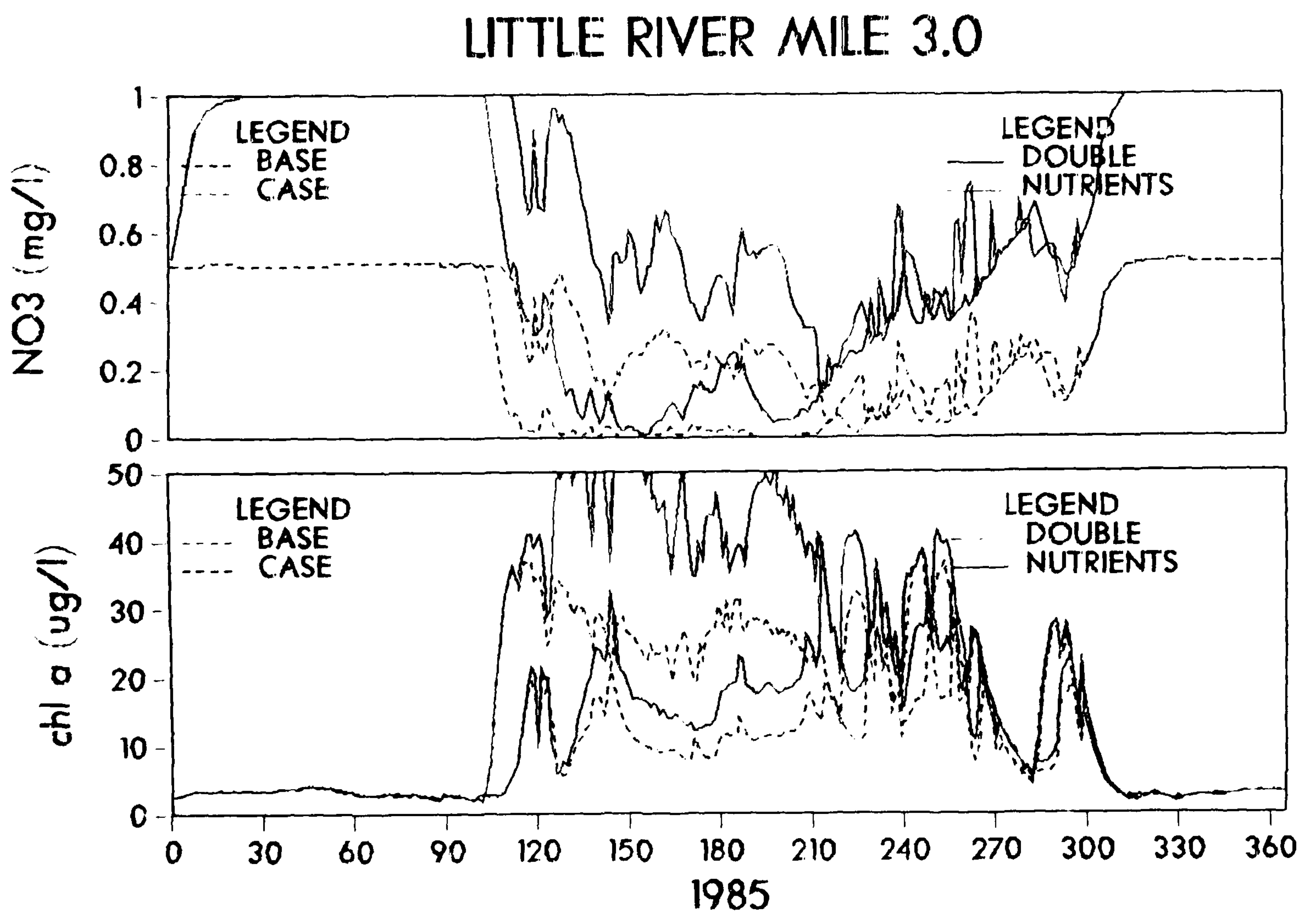


Figure 68 (continued)

the summer period by the additional algal growth. The additional nutrients allowed more uptake and produced more chlorophyll at all of the stations. The increased supply of nutrients allowed more sustained algal populations in the main channel, although the SS inflow during June still limited chlorophyll at CuRM 58.2 in June. Simulated SS inflows interrupted the increased algal activity in Eddy Creek.

The results from the reduced nutrient inflows are shown in Figures 69 to 72. Simulated DO depletion was less and some of the supersaturated surface episodes were reduced, due to the limited algal production. Surface pH values were slightly reduced, and the chlorophyll values were reduced almost to half of the base case. Since the nutrient inflow concentrations were not measured, any of these simulations might be correct. This suggests that inflow nutrients should be measured during a sufficient period of time and range of flows to establish more accurate estimates, including seasonal and flow related relationships for the Cumberland River and each of the major tributaries. These inflow nutrient measurements would be directly useful for management of non-point sources as well as point sources of nutrients to Lake Barkley.

RECOMMENDATIONS FOR ADDITIONAL MODELING AND FIELD STUDIES

The result of these investigations is a calibrated branched version of BETTER which provides an accurate characterization of water quality conditions in Barkley Lake. The model has been transferred to the Nashville District Corps of Engineers for routine use in planning and operational studies of the Cumberland River impoundments. Since water quality models of the next three upstream reservoirs are also available, it should be possible to link these models to simulate the entire 350 mile length of the lower Cumberland River from

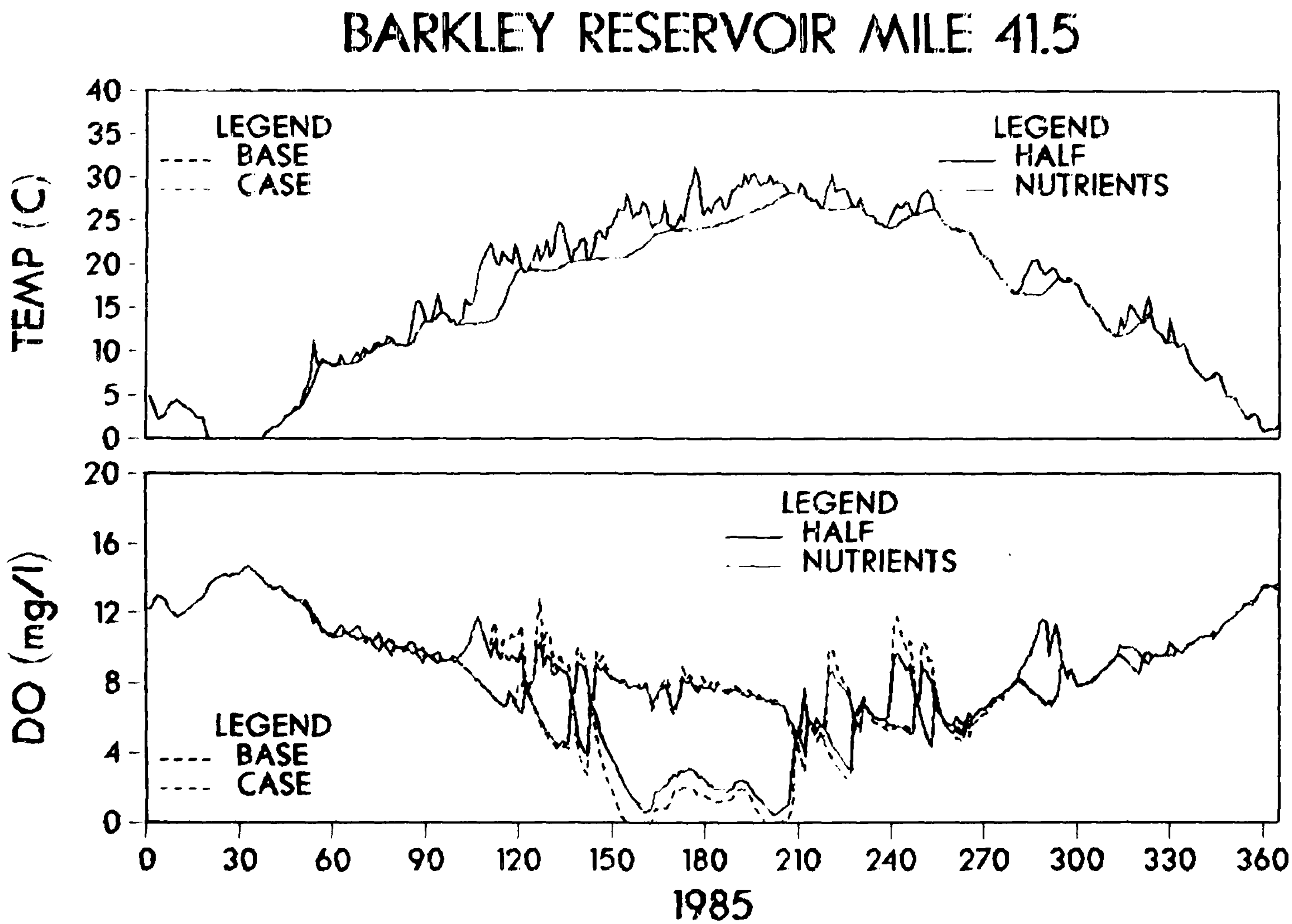


Figure 69   Simulated Effects of Reduced Nutrients at CuRM 41.5

BARKLEY RESERVOIR MILE 41.5

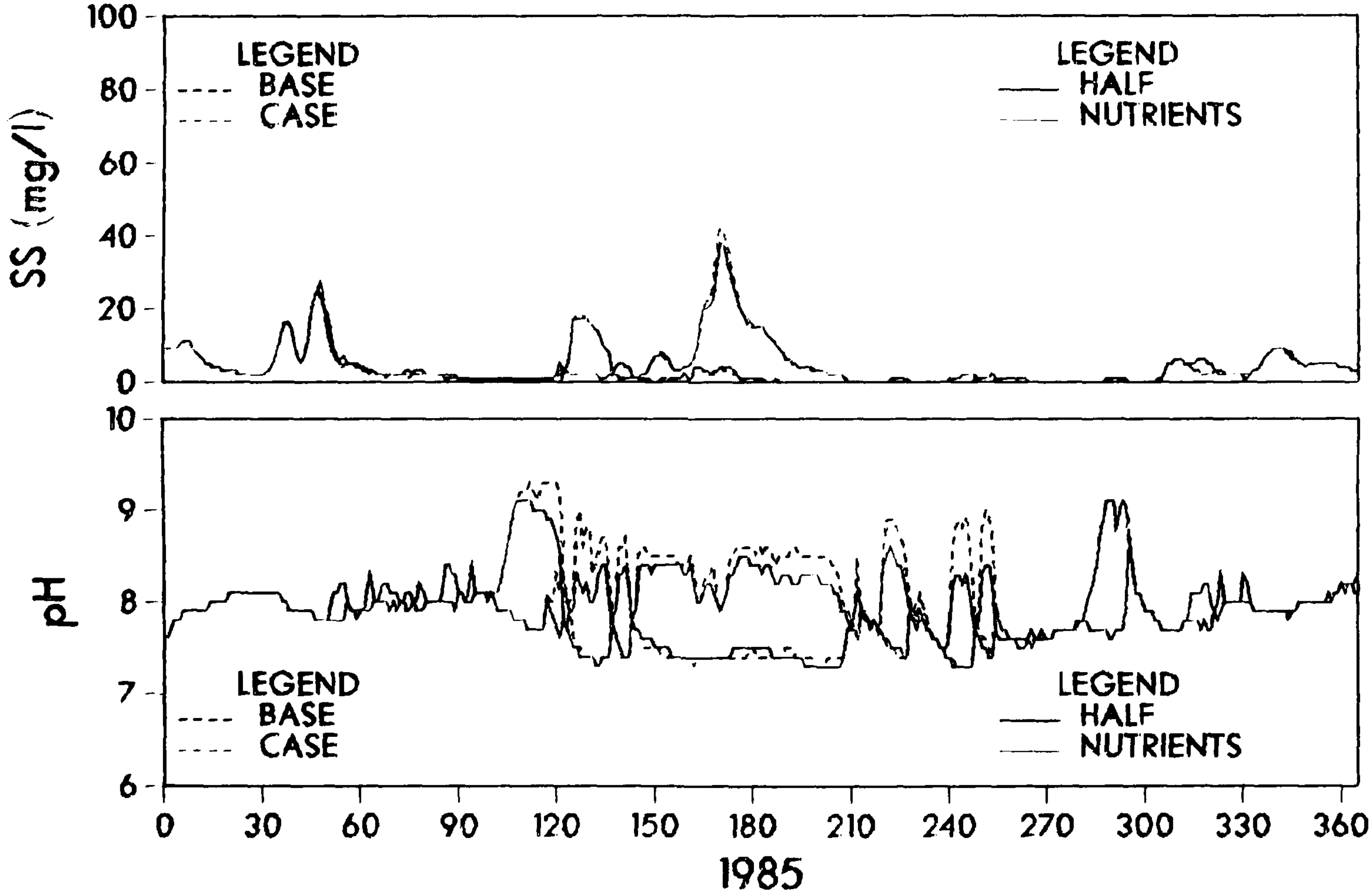
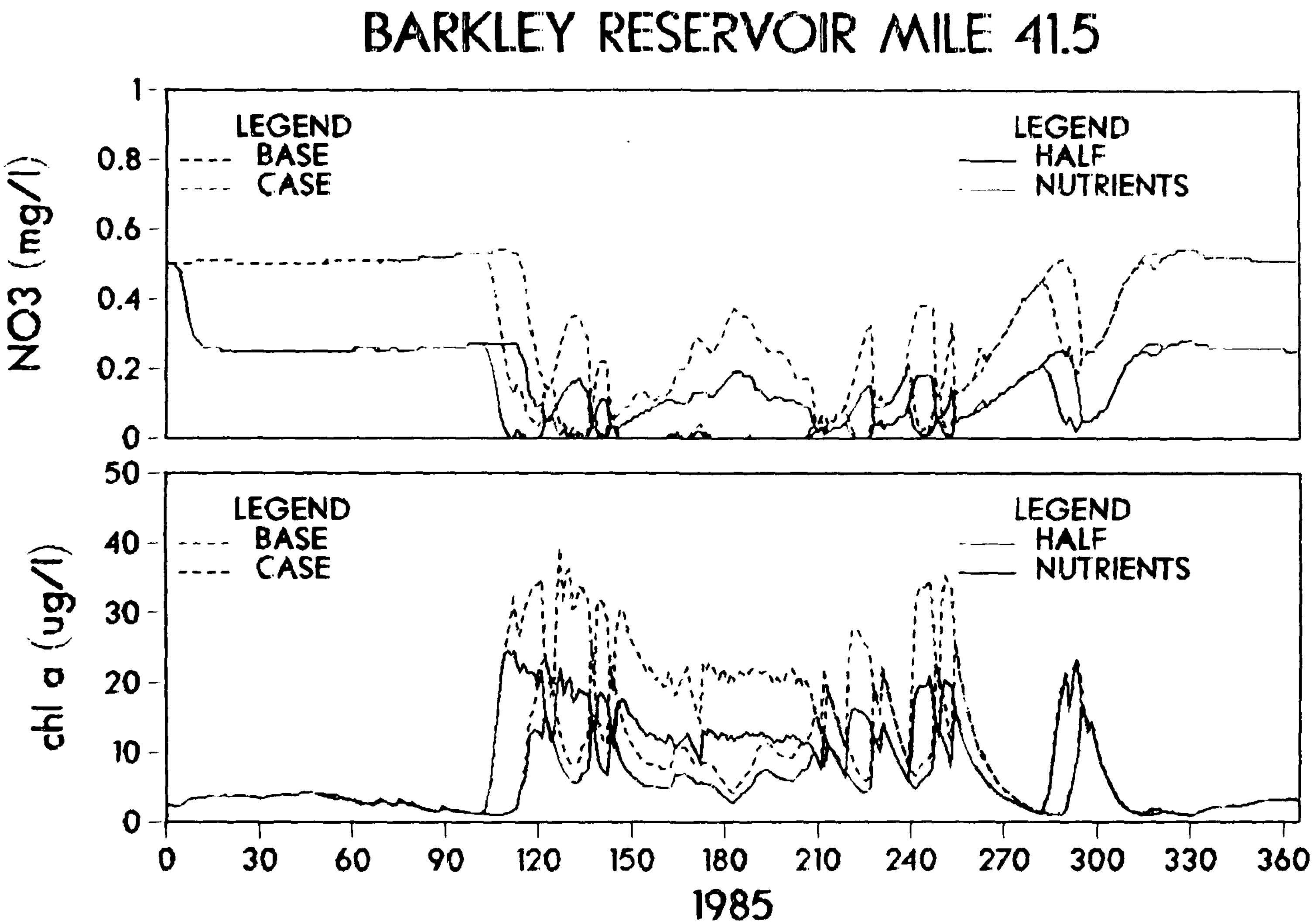


Figure 69 (continued)



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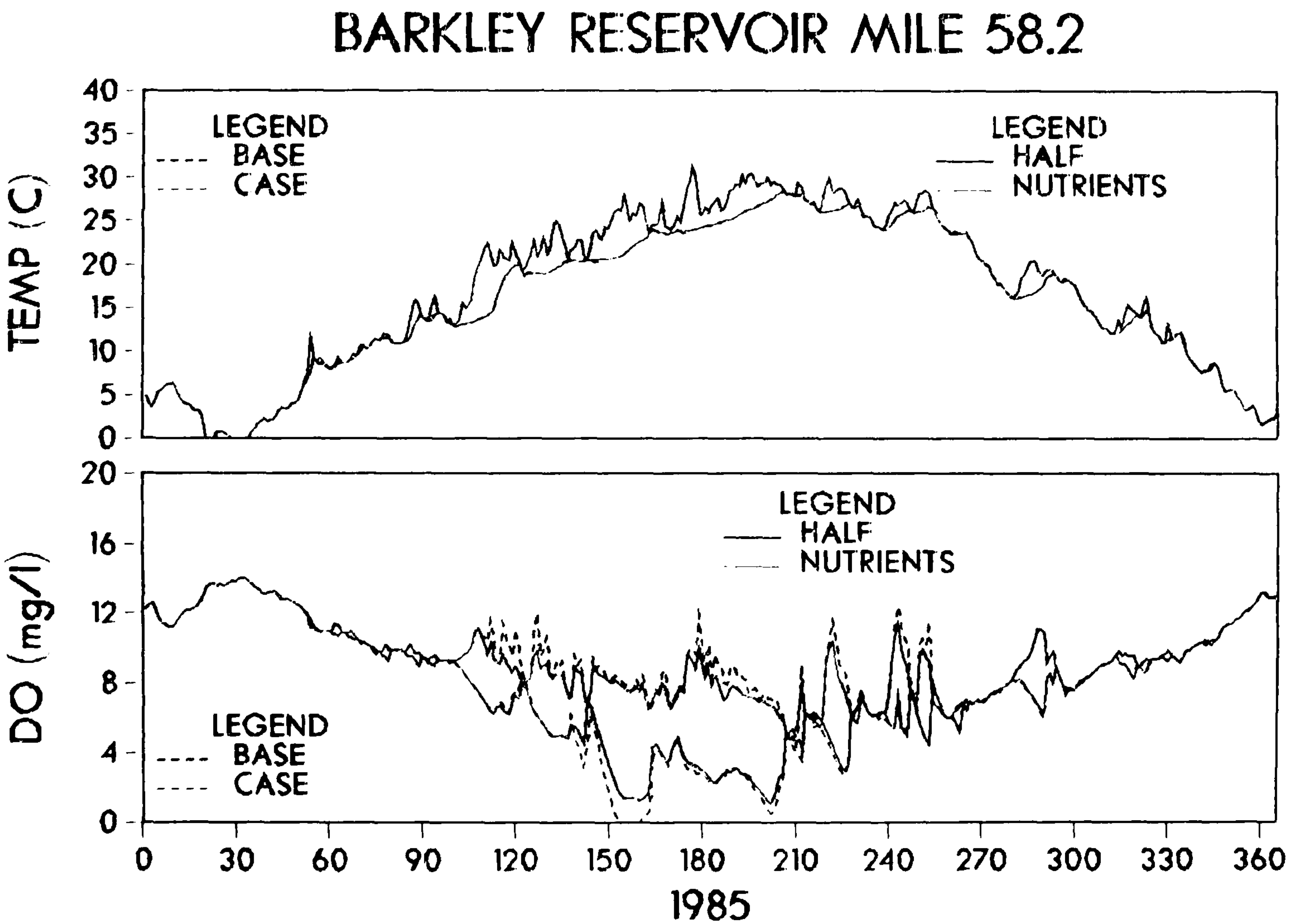
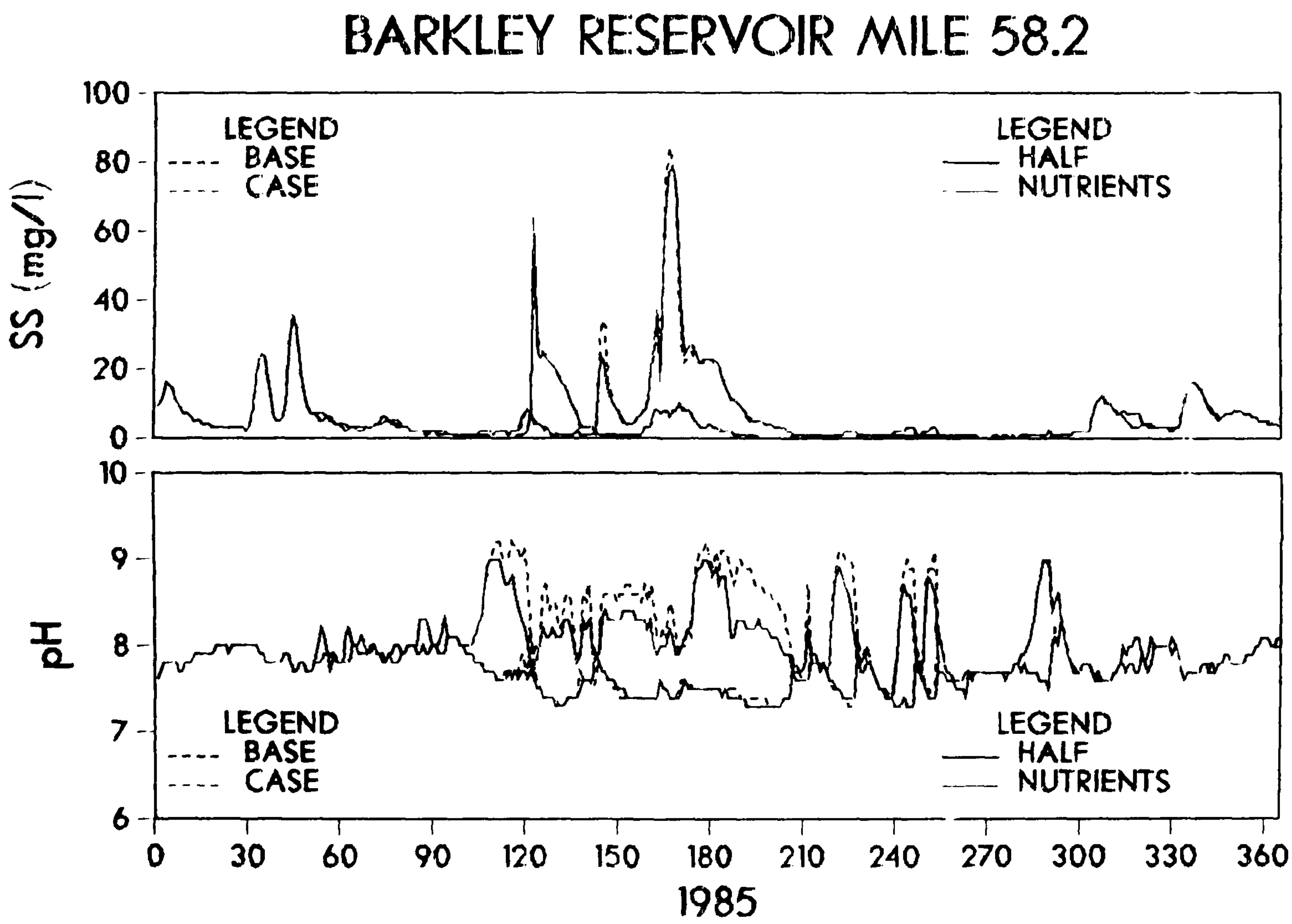


Figure 70 Simulated Effects of Reduced Nutrients at CuRM 58.2



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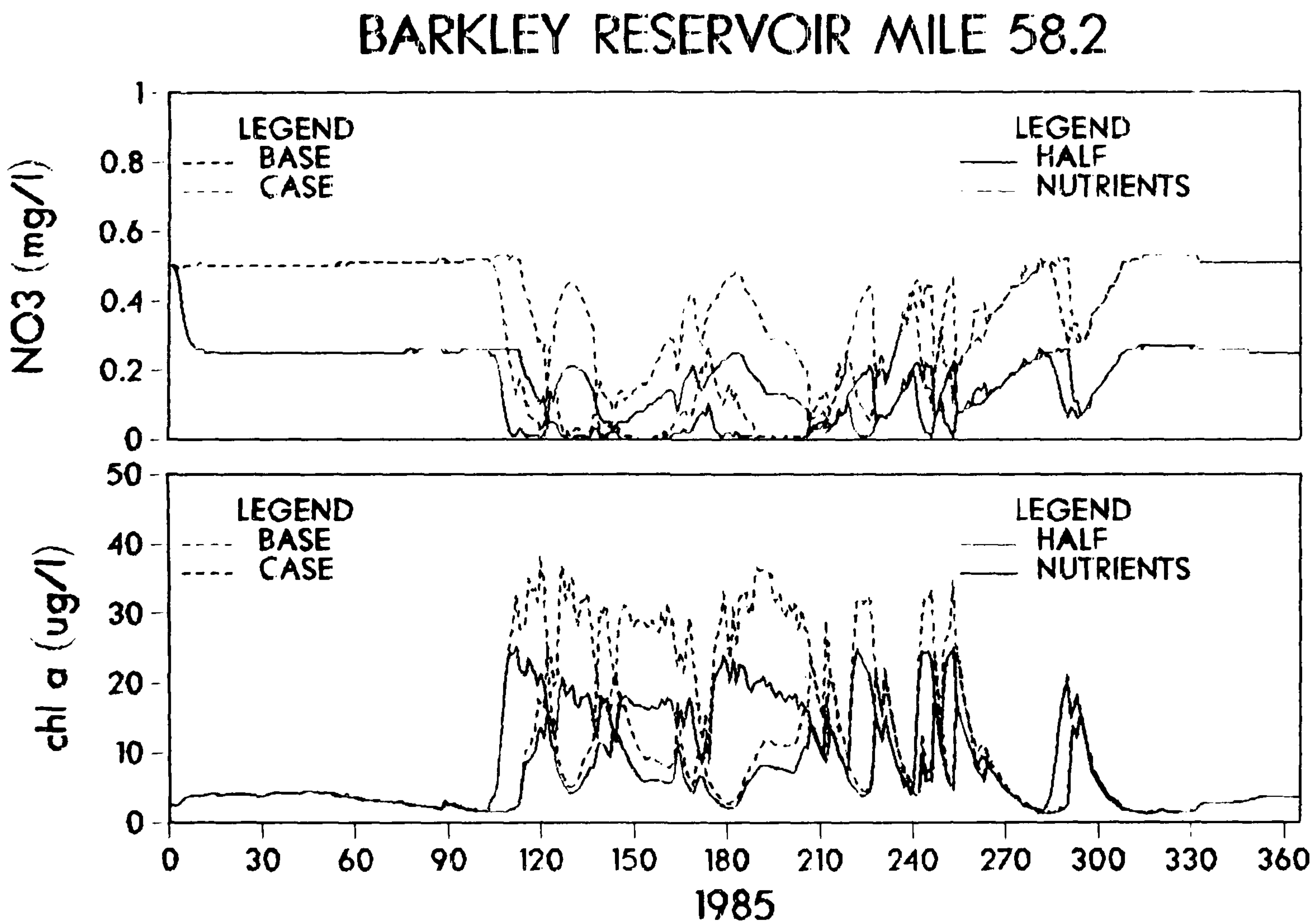

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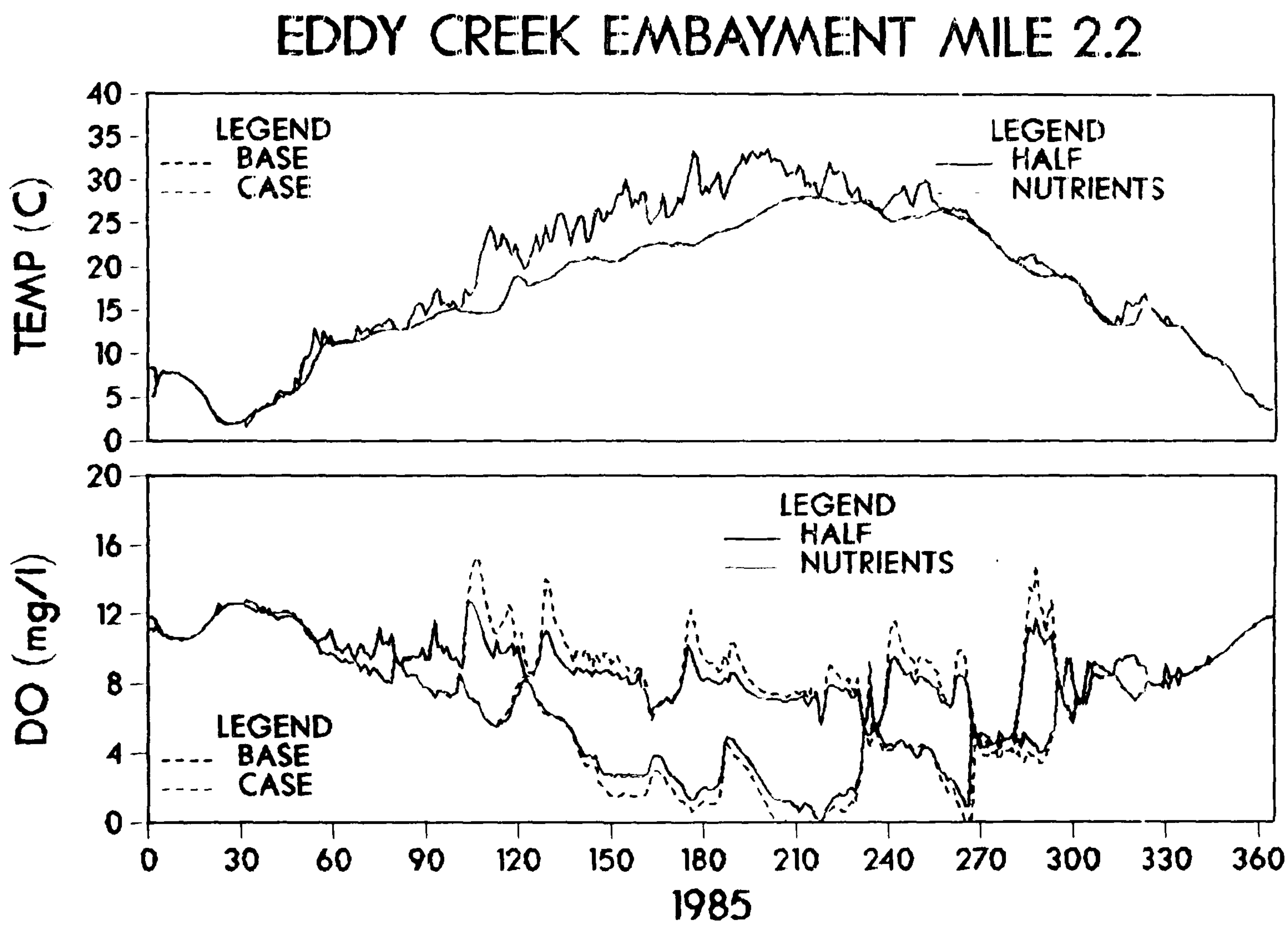
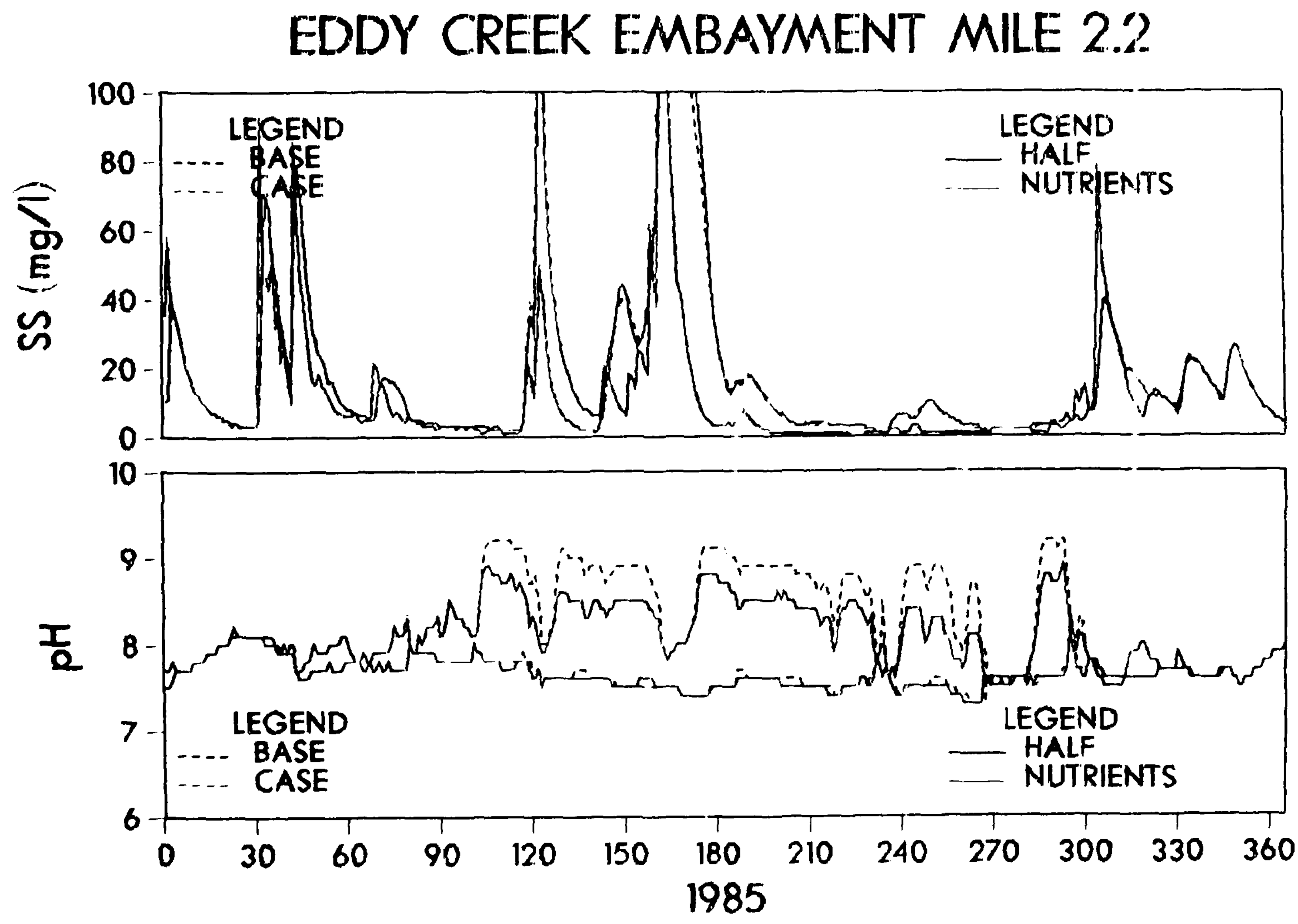


Figure 71 Simulated Effects of Reduced Nutrients at Eddy Creek Mile 2.2



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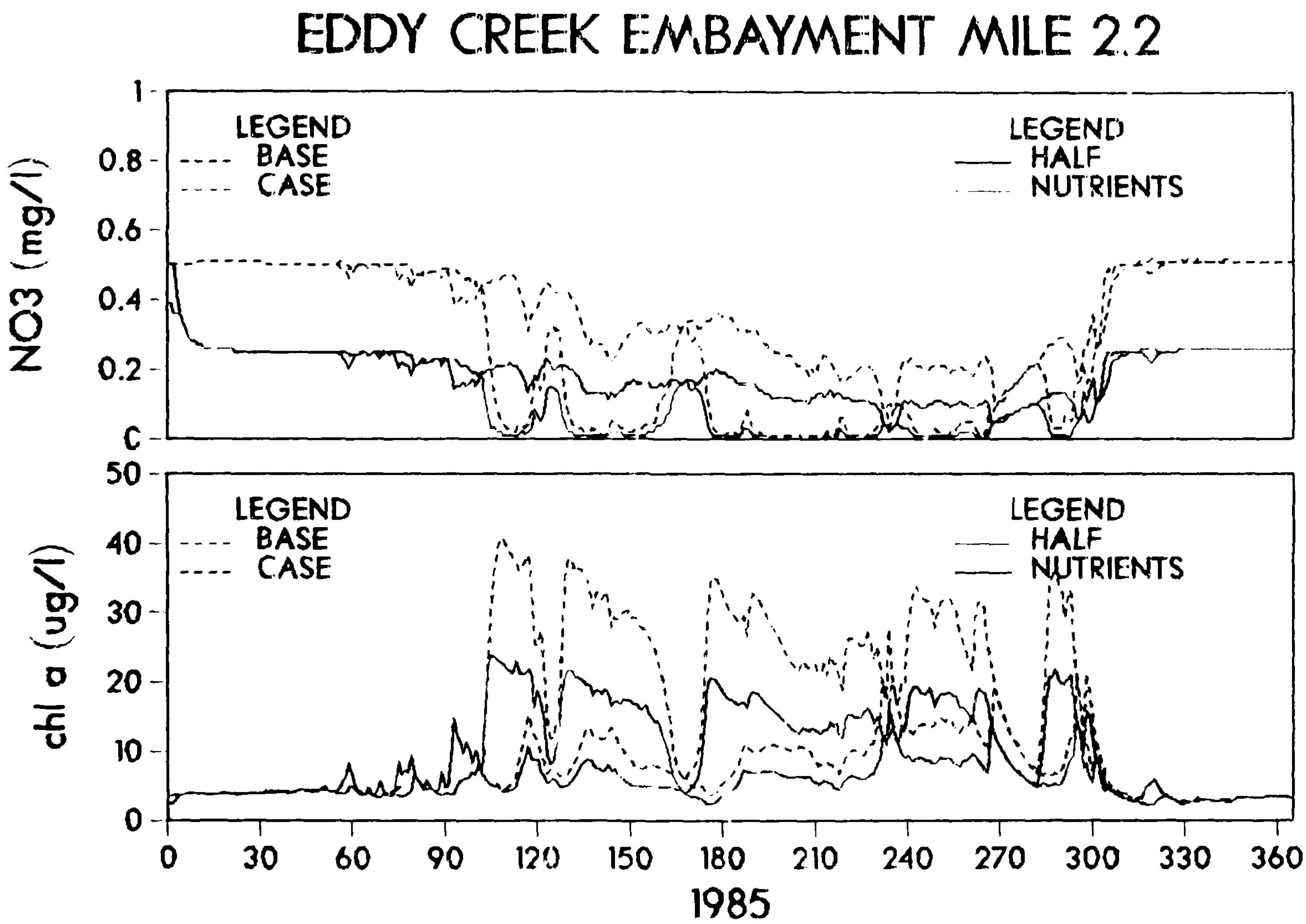

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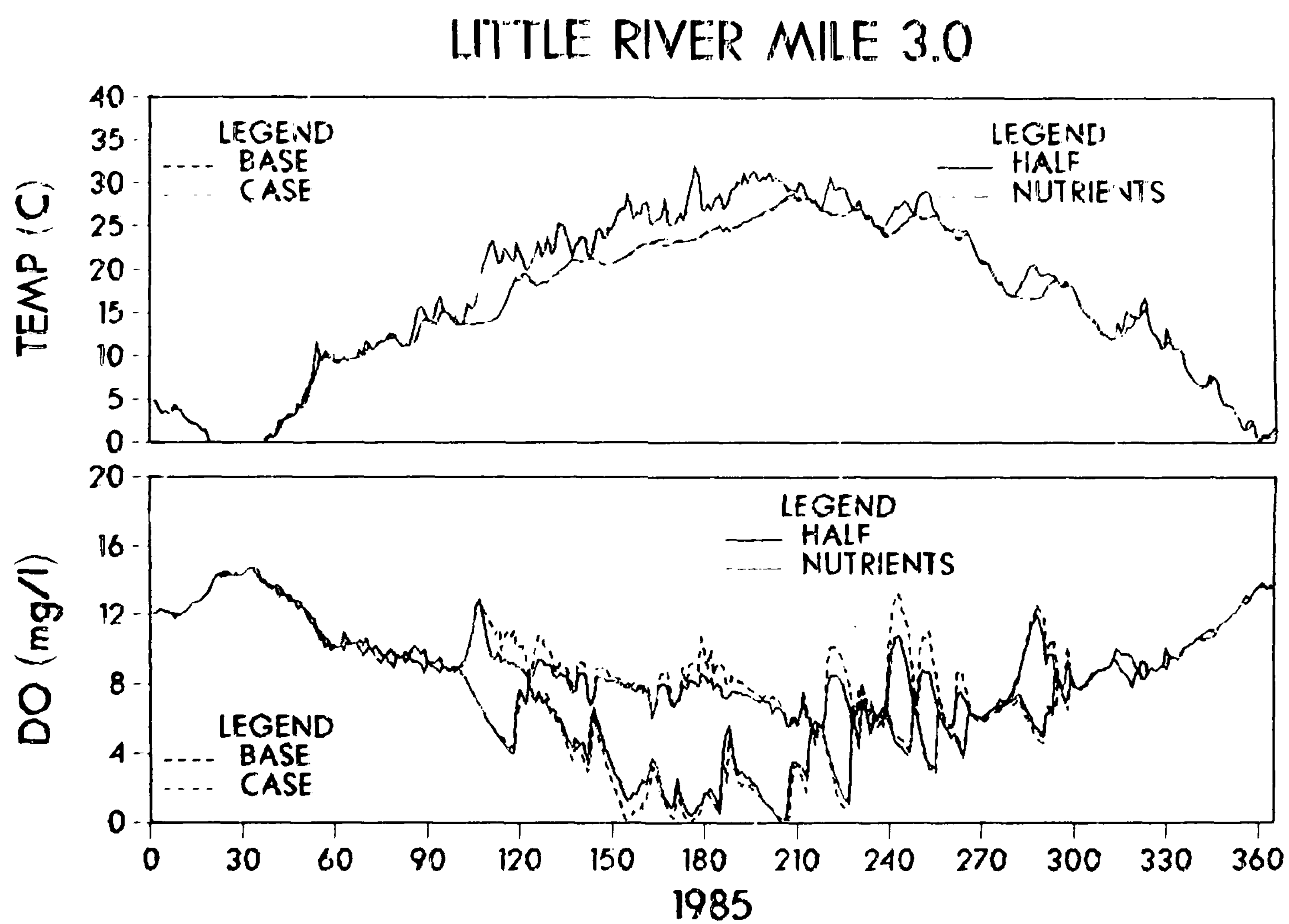

Figure 72 Simulated Effects of Reduced Nutrients at Little River Mile 3.0

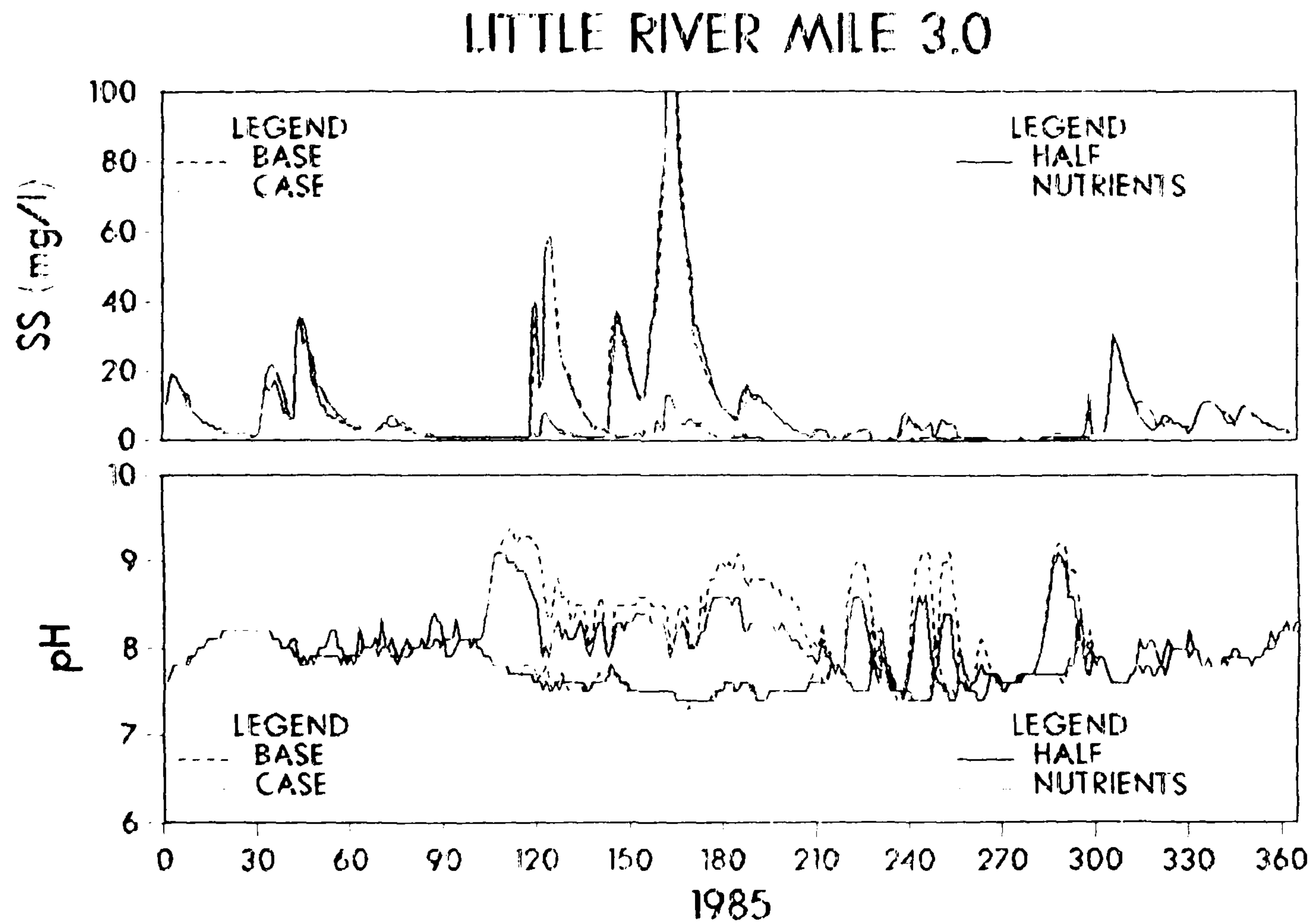

Figure 72 (continued)

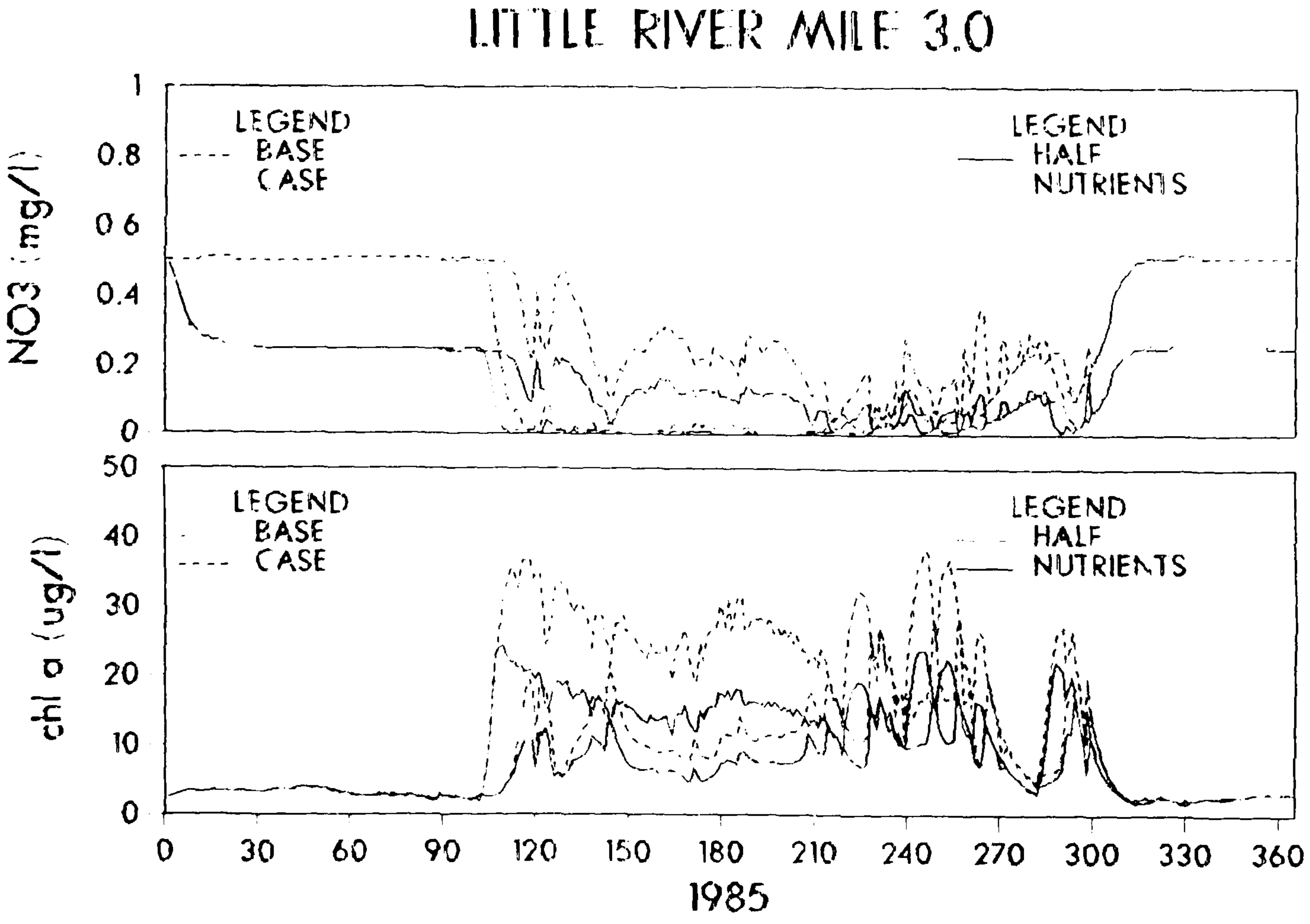

Figure 72 (continued)

Celina, TN (CuRM 380) to Barkley Dam (CuRM 30). These existing transport models could be integrated into the operational hydrology model system to provide a comprehensive water quality management tool for the Corps and other interested agencies. Future data collection activities should be coordinated to provide the most important information for model inputs and calibration checks. Much can be added to improve the model capabilities and reliability, but the existing version provides an excellent starting point for routine water quality management of the Cumberland River Basin.

Future Water Quality Data Collection Activities

The field data from the seasonal surveys of 1984-1986 provided an adequate database for calibration and validation of the branched BETTER model of Lake Barkley. Because of the intermittent stratification observed and modeled, the normal bi-weekly or monthly data collection strategies miss significant stratification and mixing events. In order to more accurately characterize the mixing regimes and vertical water quality gradients, more detailed field surveys will be required. Continuous monitors, diurnal surveys, and intensive daily sampling strategies might be utilized to obtain this data. Local wind and solar radiation data from the Cumberland Steam Plant might be used to investigate the effects of localized meteorological conditions. These field surveys will be most interesting during low flow periods, when the opportunity for stratification and intermittent mixing is the greatest.

Inflow nutrients, SS, and organic concentration measurements are generally missing for Cheatham dam releases and from the major tributary inflows to Lake Barkley. An intensive inflow survey is required to obtain more reliable inflow loading estimates. Automatic samplers, cooperative sampling at water intakes,

and storm event surveys might be used to obtain this data. This would provide an accurate characterization of external loadings to the lake, so that the effects from internal processes such as SOD and algal productivity could be more accurately modeled.

The downstream transport and settling of SS materials following major storm inflows should be investigated. Daily surveys for a week following a major storm on the main channel, and similar surveys in Little River and Eddy Creek embayments would provide this information.

The simulated algal productivity and chlorophyll patterns during the summer period should be more closely investigated with intensive light, nutrient availability, and algal productivity measurements. Continuous pH and DO measurements in combination with C-14 productivity measurements, and perhaps algal assay experiments to test nutrient responses, would be useful in more accurately representing the algal effects on water quality in Lake Barkley.

The modeling indicated that SOD rates are quite high in Lake Barkley. Field measurements or laboratory determination of SOD from sediment samples might be useful for verifying these high modeled SOD rates, or determining that some other process must be the cause of the strong DO depletion patterns observed during the 1984-1986 field surveys. Comparison between the embayment and main channel stations would be especially informative.

Improved Modeling Capabilities

The branched version of BETTER, which allows embayments to be modeled, provides an excellent tool for water quality investigations in Lake Barkley. Because of the intermittent stratification patterns, there may be some value in using hourly meteorological conditions to simulate diurnal heating, cooling,

mixing, and algal processes. Since hourly meteorological data is available from the Cumberland Steam Plant, a study to compare diurnal and daily average simulations is warranted and possible for Lake Barkley.

The modeling of embayments can be improved, since very little attention has been applied to these important regions of reservoirs up to this time. The circulation patterns in the embayments resulting from inflows and exchanges with the main channel need to be measured and characterized. Inflow temperatures must be obtained for the embayment inflows. Dye studies, and other methods of tracing flows into and out of the embayments must be used. The model indicated significant surface inflow to the embayments caused by the cooling water surface flows from the Cumberland Steam Plant. The model does not presently include convective exchange terms that might be created by surface temperature differentials between the main channel and the embayments. These exchange processes must be measured to provide the basis for improved modeling.

The present modeling of algal processes is quite generalized, and could be improved with the addition of seasonal populations of diatoms, greens, blue-greens, dinoflagellates, etc. But improved algal formulations will require more specialized data collection efforts. The possibility of contracting for this work with the Center for Reservoir Research at Murray State University is certainly worth consideration. The comparison of Lake Barkley and Kentucky reservoir water quality and algal populations might be possible, since intensive algal measurements in Kentucky reservoir are being performed routinely by Murray State.

Other biological populations, such as macrophytes, zooplankton, fish, mollusks, and other benthos might be included in the model formulations. Again, the key will be specialized data collection to support the model development

and calibration for these additional variables. Now that the general transport and mixing characteristics of the lake have been simulated, the possibilities for additional studies with the model are limited only by the imagination of those conducting the investigations. We hope that the model will provide many future benefits to the Nashville District Corps of Engineers, and others interested in Lake Barkley water quality.

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